TABLE OF CONTENTS

		Page
EXECUTIVE SUMMARY		i
1.0	INTRODUCTION	1-1
1.1	General	1-1
1.2	Objective and Scope	1-1
1.3	Contents	1-1
1.4	Personnel	1-1
2.0	LITERATURE REVIEW AND CURRENT PRACTICE	2-1
2.1	General	2-1
2.2	Geotechnical Aspects of Calcareous Sediments	2-1
2.2.1	Characterization	2-2
2.2.2	Geotechnical Properties	2-2
2.3	Current Practice	2-4
2.3.1	Pile Makeup	2-4
2.3.2	Installation Techniques	2-5
2.3.3	Load Carrying Capacity	2-6
2.4	Pile Design Methodology	2-8
2.5	Summary Remarks	2-10
3.0	IMPROVED PILING SYSTEMS	3-1
3.1	General	3-1
3.2	Approach	3-1
3.3	Overview	3-1
3.4	Conceptual Development of Various Improved Schemes	3-2
3.4.1	Backfilled Piles	3-3
3.4.2	Vibratory-Installed Backfilled Piles	3-5
3.4.3	Pressurized Piles	3-5
3.4.4	Backfilled and Pressurized Piles	3-7
3.4.5	Piles with Enlarged Tips	3-7
3.4.6	Modified Drilled and Grouted Piles	3-8
3.4.7	Wedged-in Piles	3-8
3.4.8	Drilled and Screwed Piles	3-9
3.4.9	Other Piling Schemes	3-9
4.0	SUMMARY AND CONCLUSIONS	4-1
4.1	Summary	4-1
4.2	Conclusions	4-3
5.0	REFERENCES	5-1

APPENDICES

Appendix A — Elements of Field Pile Load Tests

Appendix B — A Brief Description of the Principles of Centrifuge Tests

EXECUTIVE SUMMARY

This report presents the results of an engineering study to conceptually develop various improved piling systems for use in calcareous sediments. A literature review of current practice for designing and constructing piles in calcareous sediment was performed to provide a basis for conceptual development.

The results of literature review indicate that our knowledge of engineering behavior of calcareous sediments is meager and our understanding of pile behavior in these sediments is even poorer. Several key behavioral aspects of piles in calcareous sediments were also obtained on the basis of available experimental data and engineering judgment.

Several improved piling systems with various alternates were developed based on these key behavioral aspects with emphasis placed in practicality, achievability and following proven technique, wherever feasible. These systems include:

- backfilled piles
- vibratory-installed backfilled piles
- pressurized piles
- backfilled and pressurized piles
- piles with enlarged tips
- modified drilled and grouted piles
- keyed-in piles
- drilled and screwed piles

A detailed description and conceptual sketches of these systems are provided in the report. These systems are expected to substantially improve the load carrying capacity of piles in calcareous sediments with a high degree of predictability for transferring loads at a predetermined depth.

These developed piling systems are, to a varying extent, different from conventional piling scheme. Further development work is necessary to determine the feasibility and applicability of these systems for calcareous soil applications. Cost consideration indicates that viability and applicability of these systems should be initially determined by centrifuge tests (Appendix B) to narrow down these schemes to a selected few promising ones for subsequent field load tests (Appendix A).

It is anticipated that the promising piling schemes can be segmentized and categorized for various calcareous sediments. The ultimate goal of further developmental effort would be to achieve the ideal scenario that the pile makeup will consist of various standardized segments or features arranged to maximize load carrying capactiy in any specific type of calcareous sediments.

1.0 INTRODUCTION

1.1 General

This report presents the results of an engineering study to conceptually develop improved piling systems for use in calcareous sediments. The Earth Technology Corporation carried out the work out under the Naval Construction Battalion Center (NCBC) Requisition No. N68305-3070-24400 dated April 7, 1983, and in general accordance with NCBC's statement of work dated March 15, 1983.

1.2 Objective and Scope

This engineering study is a part of the U.S. Navy's effort to develop an improved design capability for pile construction in calcareous sediments. The objective of this study was to develop various conceptual piling systems with significantly improved axial and lateral load carrying capacities over those of conventional driven piles in calcareous sediments.

To accomplish the objective, the following scope was carried out:

1. Review of available government furnished materials (GFM) and engineering literature to provide a brief discussion of current practice for piles in calcareous soil.

2. Conceptual development of improved pile systems which could be used in calcareous sediments with a high degree of predictability for transfering structure loads at a predetermined depth.

1.3 Contents

Section 2 presents the results of our GPM and engineering literature review and a brief description of the current practice for piles in calcareous sediments. Based on the results of our review, several potential concepts of improved piling systems were developed and are presented in Section 3. Section 4 provides the summary and conclusions of this study.

NCBC's statement of work also required that a general discription of the elements involved in planning and executing a large scale field pile load test in calcareous sediments be provided. This was accomplished and the results are provided in Appendix A.

1.4 Personnel

This study was performed by Dr. Bill T.D. Lu. He was assisted by Dr. Chan Tsai who participated in the concept development work. Mr. Hudson Matlock provided continuous technical advice and review of this report.

NCBC's techical representative was Mr. Stephen C. McCarel.

Available data indicate that several engineering aspects are relevant to the behavior of piles in calcareous soils. A brief summary of various engineering aspects is provided below.

<u>Index Properties</u>

- Calcareous soils generally have lower densities and higher intra-particle voids than comparable terrigeneous soils.

- Calcareous soils contain primarily calcium carbonates and thus their grains are softer than quartz or silica sand.

- The specific gravity, G_s, of calcareous sediments is generally higher than comparable terrigeneous soils. For example, the G_s values for the calcareous sands from Florida and Guam (Noorany, 1982b) are about 2.8 or more, whereas the G_s value for quartz is about 2.65.

<u>Compressibility and Crushability</u>

- Calcareous soils are more compressible than terrigeneous soils; their compressibility results primarily from grain crushing and the collapse of grain-structure. Therefore, volume changes are generally permanent.

- Coarser-grained calcareous sediments show a more significant degree of degradation and grain crushing than finer-grained sediments.

- Grain crushing and the collapse of grain-structure can be induced by applying either confining or shearing stresses.

- Sediments with high carbonate content do not compress to as low a final void ratio as sediments with low carbonate content.

<u>Strength Properties</u>

- Calcareous soils may have higher internal friction between grain-to-grain contact than terrigeneous soils (Horne and Deere, 1962).

- Cementation may primarily affect the cohesion intercept (c) and has little effect on the internal friction (ϕ). (Frydman, 1982).

- The friction angles of calcareous soils generally decrease with increasing confining pressure. This reduction appears to be the results of grain crushing (Datta et al, 1980, 1982; Noorany, 1982b). Increasing grain crushing induces decreasing shearing resistance until a limiting value of shear resistance is reached.

- Shearing may introduce significant grain crushing and volumetric contraction.

- Even loose calcareous sediments may potentially have high internal friction angles prior to a significant degree of grain crushing. They are probably due to surface roughness and reinforcing effect of elongated or flat particles in the soil matrix (Noorany, 1982b).

- Available test results on calcareous sands indicate that prior to significant grain crushing, their internal friction angles can be higher than the values of most terrigeneous sands. Examples are shown in Table 2-1 which lists some of the test data on two calcareous sands as reported by Noorany (1982b).

- Noorany (1982b) has compared the friction angle of "natural" calcareous sands with those of partially crushed sand samples prepared at the same void ratio, and found that they are similar in magnitude.

- The soil-steel friction angles of calcareous soils as determined by direct shear tests (Noorany, 1982b) and triaxial tests (Beringen, 1982) where either the confining stress or normal stress are artificially maintained constant, appears to be independent of grain crushing.

2.3 Current Practice

As previously mentioned, our knowledge of calcareous sediments is meager. Our knowledge of pile behavior in calcareous sediments is even less. Current practice in designing and constructing piling systems in calcareous sediments is examined and evaluated below.

2.3.1 Pile Makeup

In this study, our emphasis was placed on piles in calcareous sediments for near shore and offshore applications. Such pile foundation systems usually consist of long open-ended steel pipe piles. These piles have been used by the offshore industry because they can be easily spliced, they offer a good strength to weight ratio, and they are are low displacement types, thereby reducing soil disturbance during installation and minimizing driving resistance. Long piles have generally been selected for economy, i.e., it is generally less expensive to install fewer long piles than more short piles.

2.3.2 Pile Installation Techniques

Several installation techniques are currently utilized for constructing piles in calcareous soils. These techniques are listed below in order of preference (frequency of occurrence):

- Driving with impact hammer (driven piles)
- Drilling and grouting (drilled and grouted piles)
- A combination of driving, drilling and grouting
- Drilling an enlarged base, then grouting (belled piles)
- Driving with vibratory hammers.

Existing experimental data to be described in the subsequent section (Section 2.3.3) indicate that driving by impact hammer is probably the least desirable method because it generally yields the least pile load carrying capacity among all the available installation methods. However, because that it has been successfully and conventionally used for a wide variety of soil conditions and it is simple to use, the method continues its popularity even for applications in calcareous soils.

Where rock layers and highly cemented strata are present in the sediment profile as in the Arabian Gulf and offshore Australia, piles cannot always be driven to final design penetration. Accordingly, the pile is completed by drilling to final penetration and then grouting an insert pile to form a composite pile. Alternatively, a drilled and grouted pile could be used from the outset. Pile driving has been observed to cause significant degradation of skin resistance in calcareous soils (Angemeer et al, 1975; The Earth Technology Corporation, 1983). As a result of these experiences, drilled and grouted piles are generally preferred in calcareous soils.

Belled pile foundations have been utilized for a tanker terminal project in Saudi Arabia where calcareous sediments are predominant (Burt and Harris, 1980). This method takes the advantage of high end bearing resistance in carbonate rocks or highly cemented calcareous soils.

Driving piles with high capacity and low frequency vibratory hammers has been performed for a calcareous sediment site in the Saudi Arabia (Fugro Ltd., 1982). Installation of piles by such method appears to be promising. However, little or no data are available to evaluate the effect of this installation method on the load carrying capacity of piles.

2.3.3 Load Carrying Capacity

While there exist some minimal data on the axial load capacity of piles in calcareous soils, our knowledge of the lateral behavior of such piles is practically non-existent. The following paragraphs document some of available experimental data on axial capacity of piles in calcareous sediments.

The ultimate axial compression capacity of a pile is determined as the sum of skin friction resistance, Q_s, and end (tip) bearing resistance, Q_p; and can be expressed as follows:

$$Q = Q_s + Q_p = f\ A_s + q\ A_p$$

where

f = unit skin friction

A_s = side surface area of pile, which is in contact with sediment

q = unit end bearing capacity

A_p = cross-sectional area at pile tip

Very few experimental studies have been conducted to investigate the behavior of piles in calcareous sediments. The results of static tensile pile load tests for driven piles and grouted piles in calcareous soils are summarized in Table 2-2 after Datta et al (1980). Results obtained by Angemeer et al (1973, 1975) indicated the following:

1. The skin resistance and unit end bearing of driven piles can be significantly lower than that of driven piles in terrigeneous soils.

2. The skin friction for driven piles can vary significantly from site to site. The unit skin friction resistance at the Bass Strait site ranged from about 200 to 300 psf; whereas the friction measured at the Northwest Shelf site was about 750 psf. This variation probably reflects differences in crushability, cementation and density of the calcareous soil.

3. Calcareous soils are extremely sensitive to crushing as evidenced by grouted piles potentially yielding a frictional capacity on the order of 3 to 5 times of that for driven piles.

4. Cyclic loading of a grouted pile showed no significant loss in frictional capacity after about 90 cycles. A variable loading procedure to simulate wave forces was used.

The above observed cyclic behavior by Angimeer et al (1975), appears to be contradictory to other available observations such as the work by King et al (1980). They performed small-scale (2.4-in. diameter by 8-ft long) pile segment friction tests in situ. Large displacement cyclic tests showed that the frictional resistance reduced substantially. The results of laboratory strength tests did not agree with field measurements of frictional resistance. The researchers attributed the discrepancy to sample disturbance during sampling.

The Earth Technology Corporation (1983) performed a series of experiments using a model pile driven into cemented and non-cemented calcareous sand samples. The results indicate that the behavior of piles in calcareous soils depends on a number of interrelated key parameters including grain crushability, extent of cementation and density. The major conclusions from this study are as follows:

- Pullout capacity does not correlate well with pile driving resistance.
- Pullout capacity is significantly reduced due to grain crushing.
- Crushability depends on interrelated effects of grain hardness, pile penetration resistance to driving (i.e., the amount of input energy), cement content and soil density. Crushability takes place predominantly at or near the pile wall and decreases significantly as the distance away from the pile wall increases.
- The observed low pullout capacity cannot fully be explained solely by the low values of the coefficient of friction resulting from grain crushing. Grain crushing may result in reduced lateral stress on the pile, thus leading to a low pullout capacity.
- Pullout capacity for piles in dense cemented calcareous sand can be lower than those in non-cemented calcareous sand.

The unit end bearing resistance, q, is conventionally expressed as:

$$q = q_o N_q$$

where

N_q = bearing capacity factor expressed as a function of internal friction angle, ϕ.

q_o = effective overburden pressure.

Very little data on q are reported in the literature. In addition to those summarized in Table 2-2, Figure 2-2 (Datta et al 1980) shows a plot of q as determined from field tests for piles in chalk and weakly cemented calcareous soils and the standard penetration test (SPT) resistance value, N. As can be seen from this figure, the wide scatter of data indicates that the standard penetration resistance may not be a good parameter for determining the q value for piles in calcareous soils.

2.4 Pile Design Methods

The design of pile foundations in calcareous soils is far more uncertain than for terrigeneous soils, and hence, requires significant engineering judgment. Unfortunately, little experimental information is available and the information that is available cannot be fully explained by conventional theory. The experiemental work that has been performed was discussed in the previous section.

Given the uncertainty in current design methodology, significant judgment is usually introduced in designing piles for calcareous sediments. Where important facilities are planned, it is a normal practice to conduct pile load tests to confirm load predictions. These programs are costly and time-consuming. They are usually impractical for most projects. Instead, large factors of safety are normally introduced to account for design uncertainty. However, this approach leads to costly over-design in many cases. In other situations, the large safety factor is not sufficient, resulting in unsafe design.

The following paragraphs summarize current practice in determining the axial capacity of piles in calcareous soils.

In general, current practice for determining the ultimate axial capacity of piles in calcareous sediments can be divided into the following categories:

1. Use of conventional theory with modifications to account for certain aspects of calcareous soils.

2. Empirical correlation with penetration resistance during driving.

3. Correlation with in-situ tests.

4. Correlation with full scale pile load tests.

Various features of these methods are summarized in Table 2-3. A brief discussion of these methods is provided below:

A. Conventional Theory

In this method, the conventional theory in predicting the axial capacity of piles in terrigeneous soils is used with some modifications to account for various engineering aspects of calcareous soils. Table 2-4 shows design parameters presently being used for estimating axial capacity of driven piles in calcareous sands; parameters of silica sands are also shown for comparison. Table 2-5 shows estimates of axial compressive pile capacities based on the above noted parameters for 50 and 100-meter long piles. Table 2-5 demonstrates that (1) the methods used by various consultants generally give results consistent with each other for calcareous and non-calcareous sands and (2) pile capacity for calcareous sands is only about 1/3 of that for silica sands. For piles subject to tensile loading, the capacity for calcareous soils may be as low as 20 percent of that in silica sands based on the unit friction values shown in Table 2-4 and as low as 15% based on the results of a recent laboratory study (The Earth Technology Corporation, 1983).

The design parameters in Table 2-4 do not relate the degree of cementation to measureable soil properties. Table 2-6 shows recommended design parameters correlated with carbonate content based on laboratory studies (Aggarwal, et al, 1977). These recommended design parameters are significantly higher than those used by the consultants shown in Table 2-4. Presently, lower f and q values are being used because of uncertainties associated with cemented calcareous sands and the limited data base of load tests.

Datta et al (1980) indicates that pile driving in calcareous sand results in low values of lateral pressure, sand-to-steel friction and friction angle and have recommended the design parameters shown in Table 2-7. None of the investigators or consultants have recommended parameters for cyclic loading, however.

It should be noted that the unit skin friction, f, value is often expressed as:

$$f = K\, q_o \tan\delta$$

where

K = coefficient of lateral earth pressure

q_o = effective overburden

δ = soil-pile friction angle

The K values show in Table 2-7 may be too optimistic for some calcareous soils. For example a K value of 0.4 has been utilized by Beringen (1982). The results of a model pile investigation (The Earth Technology Corporation, 1983) indicates K values can be on the order of 0.2 or less for some calcareous sands.

The design of drilled and grouted piles in calcareous sands appears to be so site-specific that recommended design parameters do not appear in the literature. The lack of progress in the development of general design procedures is undoubtedly due to the limited amount of experimental work.

B. Empirical correlation with Resistance to Driving

The empirical correlation approach essentially correlates the resistance to driving to the axial capacity of piles in accordance with empirical formula such as Engineering News Record formula. This approach has been utilized in the Navy's OBFS pier construction at Diego Garcia. The results of a recent investigation (The Earth Technology Corporation, 1983) have indicated that the driving resistance is not a good indicator for predicting the pullout capacity of piles in calcareous soils. Thus, the validity of this approach is doubtful.

C. Correlation with In Situ Penetration Tests

Standard penetration resistance has been utilized in calculating pile capacity in chalk. As indicated in Figure 2-2, this correlation yield a wide scatter of results. In addition, the poor reproducibility and potential variability of SPT results (Schmertman, 1976), this method is not recommended for piles in calcareous soils.

Beringen et al (1982) has utilized the cone penetration test (CPT) results to predict the axial capacity of piles in calcareous soils. This method is particularly promising for calcareous soil applications. However, this method in its present form does not differentiate the influence of pile installation techniques which would produce varying degrees of grain crushing and degradation in calcareous soils. Further research and development is needed.

D. Full Scale Pile Load Tests

In situ full scale pile load tests are the best methods in taking all influencing site-specific parameters into consideration. In general, calcareous sediments vary significantly in composition and engineering behavior from one location to another, and it is difficult to extrapolate results. Thus, the number of pile load tests required for calcareous soils should be larger than that for terrigeneous soils. This can be very costly. Fundamental research and development work in understanding the soil-pile interaction is necessary to reduce the required number of tests.

2.5 Summary Remarks

The results of literature review described in the preceeding sections indicate that the present design framework for piles in calcareous soils requires further improvement and development.

Although present knowledge is poor and the present practice relies heavily on empirical approaches and judgment, several behavioral aspects of piles in calcareous soils are evident or can be postulated. These include, but are not limited to, the following:

1. The skin friction resistance of driven piles in calcareous sediments can be as low as 10% of the same piles in terrigeneous soils, as indicated by the results of an investigative work performed by Ertec (1983).

2. The skin friction resistance of piles in cemented calcareous soils could potentially be less than that in non-cemented calcareous soils.

3. Pile driving-induced grain crushing increases with increasing cement content in the calcareous soils.

4. All available evidence (Noorany, 1982b; Datta et al, 1980; The Earth Technology Corporation, 1983) leads to the conclusion that the observed low skin friction resistance is indicative of the low effective lateral stress on the pile shaft.

5. Although the exact mechanism for low effective lateral stress is not clear, it can be postulated that this may be due to the following reasons (in order of significance)

   (i) Pile driving and shearing induces grain crushing which, in turn, causes soil contraction; i.e., the soils have a tendency of moving away from the pile shaft thus reducing lateral stress.

   (ii) Arching of soils around the pile shaft.

   (iii) Grain crushing might somewhat reduce the soil-steel friction.

6. The static friction angles of calcareous soils are relatively high and are comparable to those of terrigeneous sediments, prior to the occurrence of significant grain crushing. However, because their potential crushability under stress, it is anticipated that the end bearing resistances for piles in calcareous soils will be slightly less than those in comparable terrigeneous soils. It is also anticipated that there exists a limiting end bearing resistance value for piles in calcareous soils.

7. Although limited number of experimental data (Angemeer et al 1975; King et al 1980) indicated conflicting results in regards to potential degradation of skin

friction resistance (Section 2.3.3) the potential of cyclic degradation for piles in calcareous sediments cannot be ruled out. Experimental evidence for piles in clays and sands (Bogard and Matlock, 1979; Puech et al, 1982; Van Weele, 1979) suggests that skin friction of pile degrades during cyclic loading and that this degradation may not be completely recoverable. It can be postulated that cyclic degradation in skin friction would be even more pronounced for piles in calcareous sediments than that for piles in terrigeneous soils because cyclic loading would produce further grain crushing and volumetric contraction (which further reduces effective lateral stress). Cyclic degradation has been attributed to slip (shear stress) reversal (Bogard and Matlock). However, it should be noted that slip reversal may occur for cyclicly-loaded piles even though they are biased by a large dead load in one direction (Matlock and Lam, 1980). Degradation would initiate from a shallow depth and progress downward. This "un-zippering" effect could be very significant in the design of long piles in calcareous sediments.

8. Although experimental data on the lateral behavior of piles in calcareous soils are practically non-existent, it can be postulated, on the basis of relative high friction angles, that lateral load carrying capacities of piles in calcareous soils might be slightly less than or on the same order of magnitudes as those in comparable terrigeneous soils. Thus, research and development effort in understanding the behaviors of piles in calcareous soils or in developing improved piling systems should place emphasis on axial behavior. However, it should be noted that lateral behavior for piles in uncemented loose calcareous sediments could be critical. Because these sediments are meta-stable and may be liquefied upon undrained or cyclic loading, special foundation design considerations should be incorporated for these sediments and should be handled on a site specific basis.

TABLE 2-1 MEASURED FRICTION ANGLES FOR CALCAREOUS SANDS

(After Nooramy, 1982b)

Soil Type	Dry Unit Weight pcf	Void Ratio	Range of Confining Stress kg/cm^2	Range of Friction Angle, Degree
Loose Calcareous Sand from Gram	74.1	1.36	0.5 to 4	43 to 46
Dense Calcareous Sand from Gram	80	1.18	0.5 to 4	45 to 49
Loose Crushed Calcareous Sand from Gram	--	1.27	0.6 to 4	42 to 46
Dense Crushed Calcareous San from Gram	--	1.12	0.6 to 4	45 to 48
Loose Calcareous Sand from Florida	--	1.44	0.5 to 4	43 to 44
Medium Dense Calcareous Sand from Florida	--	1.30	0.5 to 4	43 to 45
Dense Calcareous Sand from Florida	—	1.19	0.5 to 4	43 to 47
Medium Dense Crushed Calcareous Sand from Florida	—	1.30	0.5 to 4	44.5
Dense Crushed Calcareous Sand from Florida	--	1.06	0.5 to 4	46 to 49

TABLE 2-2 RESULTS OF PILE LOAD TESTS IN CALCAREOUS SANDS (ADAPTED AFTER DATTA ET AL 1980)

Site	Strata	Number of Tests	f_{av} (kg/cm^2)	q (kg/cm^2)	Remarks
Bass Strait, Australia Ref. Angemeer et al (1973)	Sand, silty, showing nonuniform degree of cementation Skeletal debris crushes easily	5	0.11 to 0.16	58.6 to 97.6	Cylindrical steel pile, driven Embedded length = 45 to 82 m below mudline
North West Shelf, Australia Ref. Angemeer et al (1975)	Sandy silt to silty sand, showing varying degree of cementation, shell fragments present	1	0.38	-	Cylindrical steel pile section, driven, 11 m in a 73 m deep over-sized sleeved hole
		-	1.0	-	Drilled and grouted piles
Arabian Gulf Saudi Arabia Ref. Fuller (1979	Sand, cemented, some shells and coral fragments	3	Greater than 0.32 Pile failure did not occur	*	Concrete precast cylindrical pile, placed in an over-sized predrilled hole and driven 2 m below predrilled depth. Total pile length - 12.2 to 15.3 m below mudline

f_{av} = unit friction
q = unit end bearing
* Nq $\geq$ 40 where $q = q_o$ Nq and q_o = effective overburden pressure

TABLE 2-3 CURRENT PRACTICE TO PREDICT ULTIMATE CAPACITY OF SINGLE PILES IN CALCAREOUS SEDIMENTS

Methods	Features	Example References	Remarks
Conventional methods with modifications	$f = K q_o \tan$ $q = q_o\ Nq$ with imposed limiting f and q values and/or with higher factors of safety used in design	Datta et al (1980)	1. Limiting f and q values are empirical in nature 2. Limited experimental data base 3. Do not account for variability
Empirical correlation with penetration resistance to driving	Pile capacity is corrected to required energy to penetrate or pile head force-time history measurements during driving	Lyon Associate (1976); CWRU (1970)	1. Resistance to driving is not a good parameter in predicting skin friction resistance and uplift resistance 2. Empirical in nature 3. Disregard the true nature of grain crushing and variability in calcareous sediment 4. The potential of over or under design exists
Based on correlation with in-situ tests	Correlation with SPT or CPT results	Datta et al, 1980; Beringen et al (1982)	1. Installation effects are not differentiated 2. Lack of data bases for correlation 3. Empirical in nature 4. Site specific in nature 5. The potential of over and under design exists
Based on field pile load tests	Intepretation of field pile load tests and application of results to design	Angemeer et al (1973, 1975)	1. Data are site specific 2. Higher confidence level of use in design 3. Costly - a significant number of based tests is required for piles in calcareous sediments

f = unit skin friction resistance
K = coefficient of lateral earth pressure
δ = soil-pile friction angle

qo = effective overburden
Nq = f (ϕ), bearing capacity factor
q = unit end bearing resistance
ϕ = internal friction angle

TABLE 2-4 CURRENTLY RECOMMENDED VALUES OF DESIGN PARAMETERS FOR CALCAREOUS AND NON-CALCAREOUS SANDS (AFTER DATTA, ET AL, 1980)

Recommendations		Non-Calcareous Sands (clean, medium dense to dense)				Calcareous Sands: Degree of Cementation not specified				Calcareous Sands: Uncemented or lightly cemented				Calcareous Sands: Well cemented			
By	Year	δ	f	N_q	q	δ	f	N_q	q	δ	f	N_q	q	δ	f	N_q	q
McClelland	1974	30	1.0	40	100	30*	0.2	40*	50	-	-	-	-	-	-	-	-
API	1977	30	l.c.	40	l.c.	l.c.	l.c.	l.c.	l.c.	-	-	-	-	-	-	-	-
Consultant A	1978	30	1.0	40	100	25	0.2	20	65	-	-	-	-	-	-	-	-
Consultant B	1979	30	1.0	40	100	-	-	-	-	30*	0.3	40*	30	30*	0.6	40*	60

δ = friction angle between pile and soil, degrees

f = unit skin friction, kg/cm^2

Nq = bearing capacity factor

q = unit end bearing, kg/cm^2

l.c. = as per local conditions

*implied although not specifically stated

TABLE 2-5 EXAMPLE PROBLEM SHOWING AXIAL CAPACITIES PREDICTED BY VARIOUS METHODS FOR DRIVEN PILES IN CALCAREOUS AND NON-CALCAREOUS SANDS (AFTER DATTA, ET AL, 1980)

Based on Recommended Parameters shown in Table 4-4		Axial Capacity (Tons)							
		Non-Calcareous sands (clean, medium dense to dense)		Calcareous Sands					
				Degree of Cementation Not Specified		Uncemented or Lightly Cemented		Well Cemented	
of	year	L=50m	L=100m	L=50m	L=100m	L=50m	L=100m	L=50m	L=100m
McClelland	1974	1960	3530	630	1010	-	-	-	-
API	1977	1960	3530	-	-	-	-	-	-
Consultant A	1978	1960	3530	650	1120	-	-	-	-
Consultant B	1979	1960	3530	-	-	670	1140	1270	2220

Cylindrical steel pile of 1 m diameter

Value of K used = 0.7
γ_t used = 2.0 gm/cc
L = pile length in meters

TABLE 2-6

RECOMMENDED DESIGN PARAMETERS FOR CALCAREOUS SAND BASED ON CARBONATE CONTENT (AFTER AGGARWAL ET AL, 1977)

Carbonate content (percent by weight)	f (kg/cm^2)	q (kg/cm^2)
up to 30	1.00	100
30 to 45	0.32	80
above 45	0.28	70

f = unit skin friction
q = unit end bearing

TABLE 2-7 RECOMMENDED DESIGN PARAMETERS FOR UNCEMENTED CALCAREOUS SANDS BASED ON DEGREE OF CRUSHING (AFTER DATTA ET AL, 1980)

	Skin Friction			End Bearing	
Type	K	δ (deg)	f (kg/cm^2)	N_q	q (kg/cm^2)
Sands which crush easily	0.5	20	0.15	20	30
Sands which are resistant to crushing (medium dense to dense)	0.7-1.0	25	1.0	40	100

Notes:

(a) f = unit skin friction
K = coefficient of lateral earth pressure
δ = soil-steel friction angel
N_q = bearing capacity factor
q = unit end bearing resistance

(b) $f = K\, q_o \tan\delta$

where q_o = effective overburden pressure

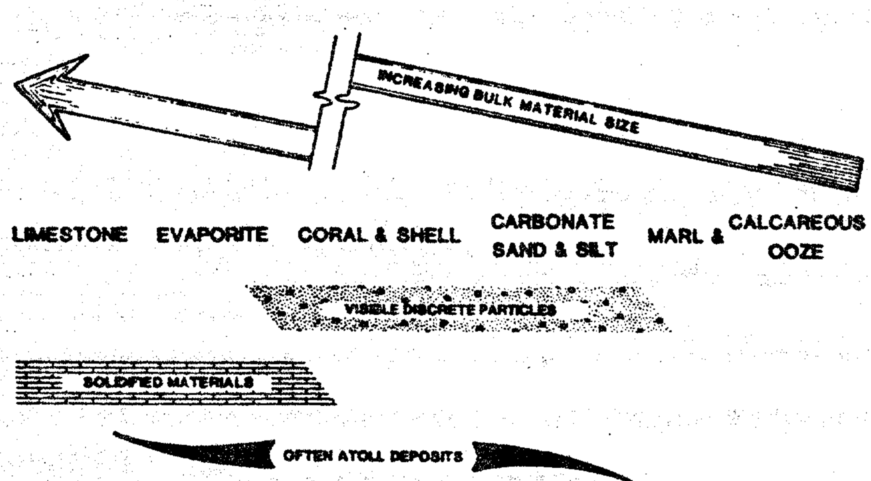


FIGURE 2-1 CATEGORIES OF CARBONATE MATERIALS AFTER ANGEMEER AND MCNEILAN (1982)

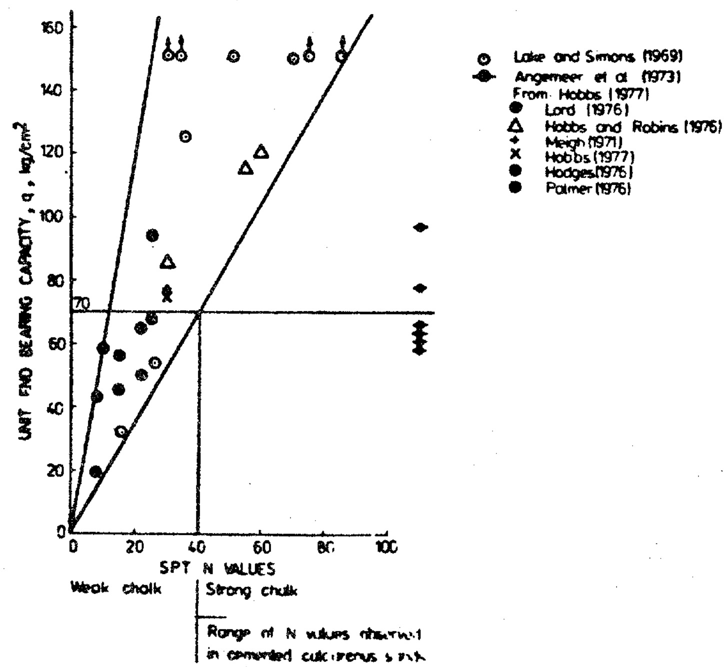


FIGURE 2-2 RELATION BETWEEN UNIT END BEARING CAPACITY AND STANDARD PENETRATION RESISTANCE IN CHALK (AFTER DATTA ET AL, 1980)

3.0 IMPROVED PILING SYSTEMS

3.1 General

In the conceptual development of improved piling systems in calcareous soils emphasis was placed upon potential applications to a wide variety of calcareous sediments. However, it should be noted that foundation design in calcareous limestone regions, where notable (sizable) sinkholes, cavities and solution channels exist, is in general, site specific in nature and is not covered in this study. Foundation types other than piles may be more appropriate and economically feasible under such conditions.

Various conceptual schemes were developed on the basis of the current understanding of the pile behavior in calcareous sediments. Because the behavior of piles in calcareous soil sediments is complex and our understanding meager, it was necessary to postulate various behavioral aspects on the basis of engineering understanding and judgment. Thus, attempts were made to extend beyond the state-of-the-art and thereby some of the developed schemes may inevitably involve a varying extent of risks and development work in order to prove their viability.

3.2 Approach

In developing the improved piling systems for calcareous sediment applications, the following principles were implemented:

1. Recognize the various special behavioral aspects of piles in calcareous soils based on our knowledge.

2. Postulate the mechanisms behind these aspects in accordance with good engineering judgment and assumptions if the knowledge is nonexistent.

3. Improve various behavioral aspects which yield low load carrying capacity, and maintain or enhance various behavioral aspects which yield relatively high load carrying capacity similar to those in comparable terrigeneous soils.

4. The improved pile systems developed should be practical, achievable and involve minimal risk and development.

5. Whenever feasible, proven techniques which have been successfully applied elsewhere, should be implemented in the development of improved piling systems.

3.3 Overview of Conceptual Development Effort

The first two principles of the above were followed and are documented in Section 2. Installing piles in calcareous sediments and subsequent loading will introduce a varying degree of grain crushing and volumetric contractions near the pile shaft. The extent of grain crushing and volumetric contraction depends on piling scheme, installation method, characteristics of calcareous sediments, the state of stress, loading characteristics and other factors. Various key behavioral aspects of piles in calcareous sediments were identified and are described in Section 2.5.

Upon examination of key behavioral aspects, it is clear that any improved piling systems should incorporate one or a combination of the following features:

1. Increasing the effective lateral stress on pile shaft.

2. Forcing the pile to transfer load to the zone of soils where degradation due to grain crushing is minimal.

3. Enlarging the base area.

4. Eliminating or reducing the effect of grain crushing and associated volumetric contraction as well as soil arching.

5. Increasing contact area between pile and sediments.

There exist numerous variations of piling schemes which can incorporate one or a combination of the above features. Most of the conventional piling systems (expect driven piles) described in Section 2.3.2 have incorporated some of the above features. They are generally costly and are out of the scope of this conceptual development work. The next section describe some of the developed concepts which are considered promising. Conceptual sketches and relevant remarks are also provided.

3.4 Conceptual Development of Various Improved Piling Schemes

The following improved piling systems were conceptually developed following the approaches and principles described in the previous sections:

1. Backfilled piles (BP)
2. Vibratory - installed backfilled piles (VBP)
3. Pressurized piles (PP)
4. Backfilled and pressurized piles (BPP)
5. Piles with enlarged tips (PET)
6. Modified drilled and grouted piles (MDGP)
7. Keyed-in piles (KIP)
8. Drilled and screwed piles (DSP)
9. Other potential piling systems.

The above conceptual piling schemes are, to a varying extent, different from conventional piling systems. They were developed based on our understanding, various postulations and engineering judgment. These schemes and their effectiveness in improving load carrying capacity in calcareous sediments are yet to be proven. In addition, most of the procedures and equipment required for deploying these "improved" piling systems need some amount of further development.

Some of the piling schemes are presented with various alternates depending on site conditions and applications. The following sections provide a description of these piling systems.

3.4.1 Backfilled Piles (BP)

As shown in Figures 3-1 to 3-3, this concept consists of installing the pile in an oversized hole and then backfilling the annulus between the pile and the hole with granular materials. The granular material can be densified by internal underwater vibrators or by vibration force provided from the pile top or by other means. The procedure is very similar to the drilled and grouted piles except granular materials are used instead of grout.

Using granular materials as backfill offers the following advantages:

1. It increases effective lateral stress on the pile shaft. Thus, it increases the skin friction resistance, and

2. Eliminates grain crushing and soil arching effect in the calcareous soils.

3. Fills the cavities with granular materials.

There are several alternates which are capable of completing an oversized hole. They are described as follows.

<u>BP Alternate A - Conventional Drilling</u>

As shown in Figure 3-1, the oversized hole can be drilled by conventional drilling techniques. For noncemented or lightly cemented calcareous soils, drilling mud may be required for the stability of drilled hole. In this case, granular maerials in the forms of sand slurry can be pumped under pressure to force out the drilling mud.

Further research and development work is necessary for this alternate scheme. This includes the following:

1. The types of granular materials suitable for use as backfill.

2. The extent of potential mud contamination and its effect to the granular backfill and pile capacity.

3. Appropriate procedures and equipment to place and densify the granular materials.

4. Optimal sizing of the backfilled annulus to minimize the effects of soil arching on the lateral stress.

5. The pile behavior under static and cyclic loadings.

It should be noted that this concept is particularly applicable to cemented or solidified calcareous sediments, where the drilled hole will stay open without the use of drilling mud. Pile installation under such conditions is relatively simple and straight forward.

BP Alternate B - Cased Drill Hole Using a Withdrawal Tube

Drilling mud contamination can potentially reduce the load carrying capacity significantly. To avoid this complication, an alternative scheme which eliminates the need of drilling mud is possible. This alternative scheme (Figure 3-2) involves the following:

1. Attach a drill bit to the tip of a withdrawable tube slightly smaller than the oversized drilled hole.

2. Simultaneously advance the drilled hole and the tube until a predetermined penetration depth is reached.

3. Withdraw the drill bit while holding the tube stationary.

4. Insert the pile using a centralizer.

5. Place (or pump in) granular materials in slurry form into the annulus between the pile and the wall of the oversized hole.

6. Gradually withdraw the tube and use the tube to compact (densify) the granular backfill at regular intervals while withdrawing.

7. Complete the pile installation to the sediment surface then withdraw the tube.

BP Alternative C - Driving a Withdrawal Tube with an Expendable End Plate

This concept is similar to Alternate B except the oversized hole is created by driving a withdrawal tube with an expendable end plate attachment (Figure 3-3). After the hole is driven to the predetermined depth, pile insertion, backfilling and compaction are achieved following the same procedures as those described for Alternate B.

Remarks

The development work required for Alternates B and C are similar to those described for Alternate A with the exception of drilling mud concerns.

3.4.2 Vibratory-Installed Backfilled Piles (VBP)

This concept can also be used to avoid using drilling mud in non-cemented and lightly cemented calcareous sediments. As shown in Figure 3-4, this piling scheme involves the installation of an inverted and slightly tapered pile by vibratory hammers. The gap between the tapered piles and hole created by the penetration of pile tip can be simultaneously filled with granular materials from a supply reservoir or by pumping in granular (sand) slurry. Vibratory hammers in this case are utilized to penetrate the piles and to densify the backfill materials at the same time.

Again, the procedures and equipment to install this scheme require further development. However, the effort is expected to be minimal. Further development work as described for the BP scheme (with the exception of drilling mud effect) is also needed.

3.4.3 Pressurized Piles (PP)

This concept involves the artificial imposition of a high lateral stress on the pile shaft. This can be achieved by several ways:

1. Installation of specially designed piles which can be expanded through hydraulic or mechanical systems.

2. Using explosives to force the pile shaft to expand outward and key into the sediments as well as cavities, if any.

3. Expansion of weak pile segments by excessive driving force.

PP Alternate A

The first alternate, in general, involves the installation of an expandable pile consisting of two overlapping half sections as shown in Figure 3-5. Pile installation can be achieved by either impact hammers or drilling and inserting. Either hydraulic pressure or mechanical systems can be deployed to force the pile to expand outward. There are potentially a number of systems which can be designed for this purpose. The criteria for selection should be based on cost and complexity of applications. Two example mechanical systems ar shown in Figure 3-5.

PP Alternate B

The second alternate (Figure 3-6) involves the use of explosive charges at regular intervals and at locations where cavities are adjacent to the pile shaft. The pile in this case can be the regular tubular steel type (either open ended or close-ended).

The explosive is detonated after the pile is installed by a impact hammer or by drilling and inserting procedures, vibratory hammers or jacking forces. A special pile cap may be required to maximize the blasting effect. Explosion will expand portions of the pile wall to key into the sediments or the voids in the cavities, thus increasing the lateral pressure on the pile shaft as well as creating racheting contacts with the cavity walls when the pile is subject to axial compression or uplift (i.e. increasing skin friction resistance).

In the pressurized pile scheme, the structural integrity of piles during installation, pressurizing and loading has to be carefully considered in the design.

PP Alternate C

This alternate involves the installation of specially designed and fabricated, open-ended piles consisting of segments of weak sections (by slotting the piles or utilizing smaller wall thickness) as shown in Figure 3-7. Pile installation is achieved by either impact hammers or drilling and inserting procedures. If impact hammers are used, it is important to ensure that impact energy is sufficient to install the pile to the predetermined depth, yet in the meantime, is low enough not to damage or yield the weaker segments (section) of the pile. After insertion, a higher impact energy is applied to the pile to buckle the weaker segments and force them to key in the sediments or cavities, if any.

Remarks

The above PP alternates are unconventional to say the least. A substantial development effort in pile design, installation procedures and confirmation work in their load carrying capacity is needed.

3.4.4 Backfilled and Pressurized Piles

This version is a combination of BP and PP or VBP and PP. In other words, the BP or VBP are installed first then pressures or expansion applied.

3.4.5 Piles with Enlarged Tips (PET)

The principle of this concept is similar to the belled piles commonly used in the industry to achieve an increased end-bearing resistance or uplift capacity. However, belled piles for near shore and offshore applications are very costly and time consuming. The PET developed in this study basically follow the proven techniques used on land. Two alternates were developed and are described below.

Alternate A - Piles Installed With a Withdrawable Tube

Figure 3-8 shows a conceptual drawing for this system. This system is very similar to the Franki piles, the Alpha piles or the pedestal piles (Tomlinson, 1977). As shown in this figure, installation of this system involves the following steps:

1. Lower the withdrawable tube to the sediment surface.
2. Pour in gravel or concrete cement to form a plug at the bottom of the tube.
3. Drive the tube down by applying blows from an internal drop hammer acting on the plug.
4. After reaching the pre-determined penetration depth, hold the tube stationary and pour in sufficient amount of concrete.
5. Use internal hammer on concrete to form a bulb (expanded) end.
6. Place the pile and an internal hammer, and drive the pile into the blub end.
7. Use the internal hammer to compact successive charges of concrete or grout or granular backfill while withdrawing the tube.
8. Complete the pile installation to the surface then completely withdraw the tube and hammer.

This piling system can be easily installed in most calcareous sediments except in highly solidified calcareous rock (such as limestone). Since similar techniques have been successfully deployed elsewhere, it is anticipated that this piling system can be readily deployed for calcareous sediment application with minimal development effort. The development effort should be concentrated on understanding the pile-sediment mechanisms and the verification of load carrying capacity increase.

Alternate B - Modified Belled-Piles (MBP)

This system differs somewhat from the conventional belled piles as illustrated in Figure 3-9, the procedures involved (1) installation of a regular open-ended steel pile by either impact hammer or vibratory to a predetermined depth (2) removal of the internal plug, (3) insertion of an internal expandable drill bit to underream a belled end and then withdrawal, (4) placement of cement or grout in the belled end through the pile, (5) seating the pile into the belled end by hammers or other means, and (6) placement of cement or concrete to complete the pile installation.

The equipment to take out the internal plug and to form a belled end is available and can be easily adapted for this scheme.

3.4.6 Modified Drilled and Grouted Piles (MDGP)

As shown in Figure 3-10, this concept is a slightly modified version of the conventional drilled and grouted piles. The pile wall in this scheme is perforated and a slightly oversized drill bit is attached at the tip of the pile. This concept involves (1) advancing the pile and drill bit at the same time (no drilling mud is used, thus avoiding mud contamination), (2) withdrawing the drill bit after a predetermined penetration depth is reached, and (3) placing pressurized grout from inside of the pile through the predrilled hole to fill the annulus. In some occasions the hole may collapse during drilling and thus prevent the advance of pile insertion. Thus it may be necessary to apply either vibratory or impact forces from the top to advance the piles.

3.4.7 Keyed-in Piles (KIP)

As shown in Figure 3-11, this concept incorporates a specially designed pile with a mechanical keying-in system equipped with lateral extension branches which can be pushed through the piles and into the surrounding sediments after the pile is driven or installed by vibratory hammers to a predetermined penetration depth. Either hydraulic or mechanical systems can be utilized to push in the extension branches. Upon axial loading, the extended branches force the formation of a different and more complicated failure pattern in the soil than that of conventional piles. Additional load carrying capacity in either axial compression or pullout is expected for this scheme.

A substantial development effort is needed for general application of this piling system. Several aspects require further evaluation. They include, but are not limited to, the following items:

1. Understanding the failure mechanism governing the load carrying capacity of this piling system in a variety of calcareous sediments.

2. Effects of various configurations of the keying-in system on the axial behavior of this piling system.

3. Design and implementation of keying-in system and pushing-in system.

3.4.8 Drilled and Screwed Piles

This concept is very similar to the Fundex piles used in Europe (Tomlinson, 1977). This concept (Figure 3-12) essentially involves the following installation steps:

1. An expendable helically-screwed drill point is held by a bayonet joint to the lower end of a piling tube.

2. The tube is rotated by a hydraulic motor or rotary table at the same it is forced down by hydraulic rams.

3. After reaching a predetermined penetration depth, the pile is inserted onto the expendable drill point.

4. Grout (i.e. drilled and grouted pile), granular materials (i.e. backfilled piles) or concrete is then poured into the annulus then the tube is withdrawn.

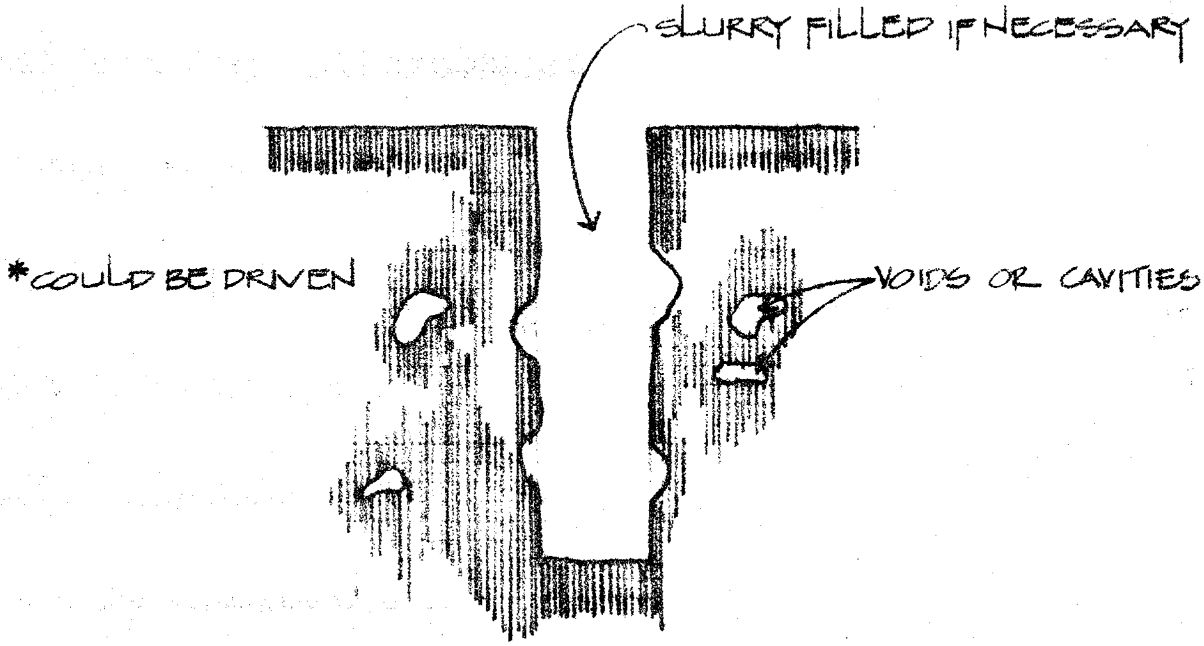
5. While withdrawing, the tube can also be used for compacting the backfill material.

The techniques and equipment for this concept have been deployed elsewhere. It is expected that the effort required to develop necessary installation equipment and techniques for this concept will be minimal. However, the extent of improvement in its load carrying capacity require further evaluations and confirmation.

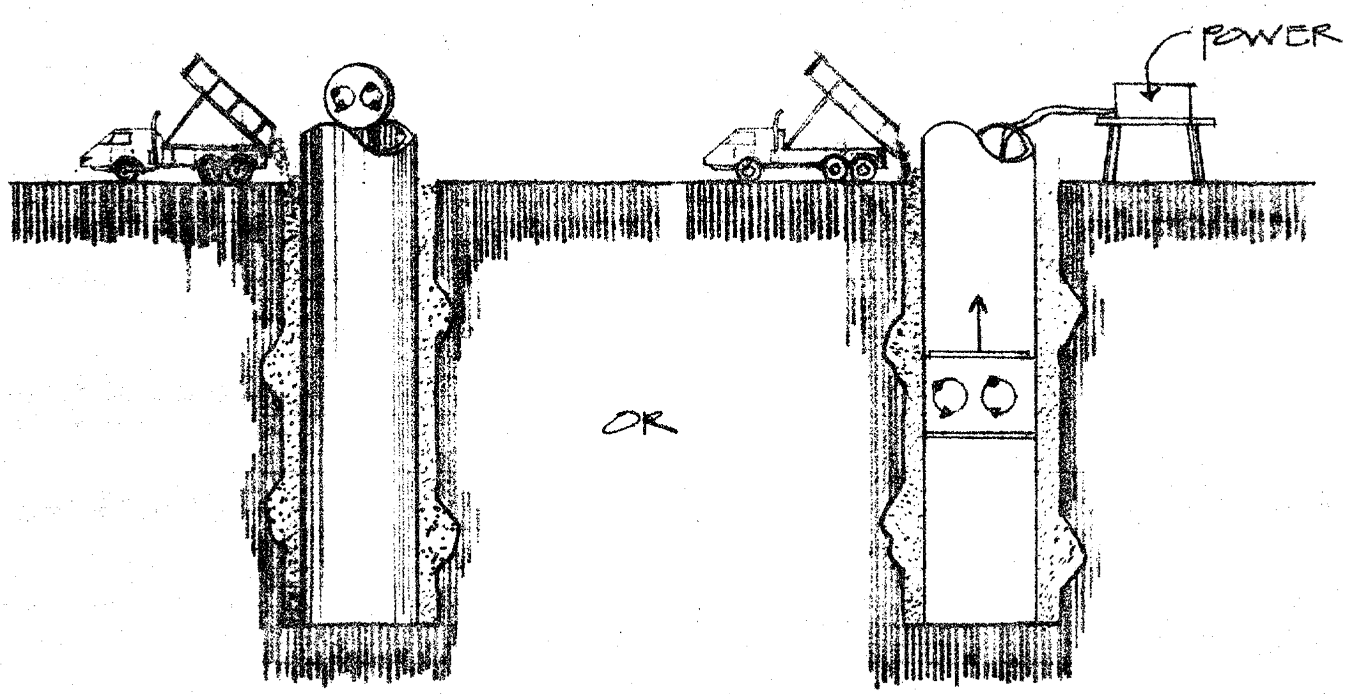
3.4.9 Other Piling Schemes

The above concepts are some of the promising ones. These concepts are flexible and some of them can be combined to form new piling systems. Other piling schemes such as sheet piling (increasing shaft contact area) and concepts similar to the wall anchors commonly in household use are also potentially viable.

BACKFILLED PILES - ALTERNATE A



STEP 1: DRILLING AN OVERSIZED HOLE



(A) TOP-MOUNTED VIBRATOR (B) INTERNAL MOUNTED VIBRATOR

STEP 2: INSERTING PILE, PLACING AND COMPACTING BACK-FILL MATERIALS

FIGURE 3-1 CONCEPTUAL DRAWING OF A BACKFILLED PILE - ALTERNATE A

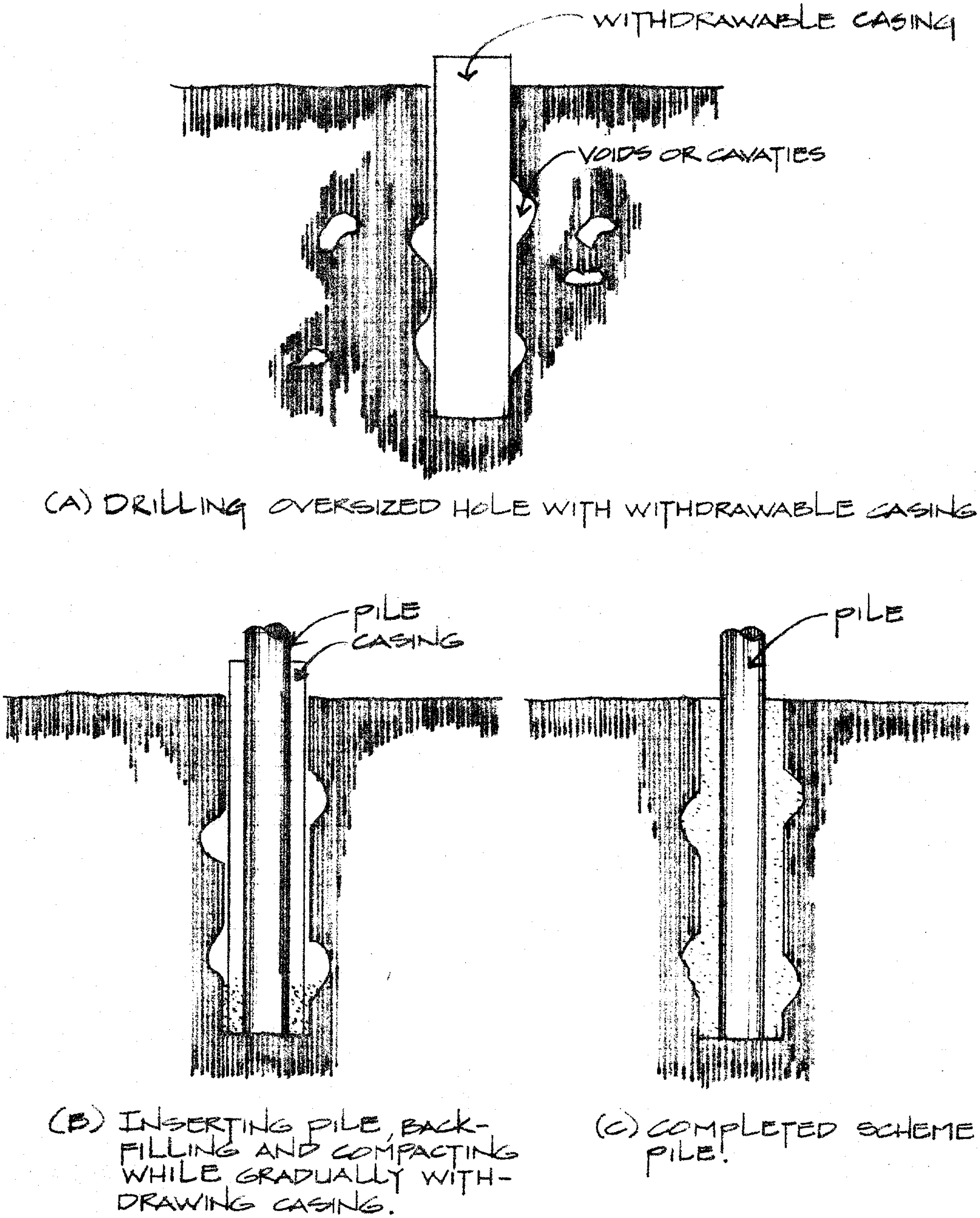
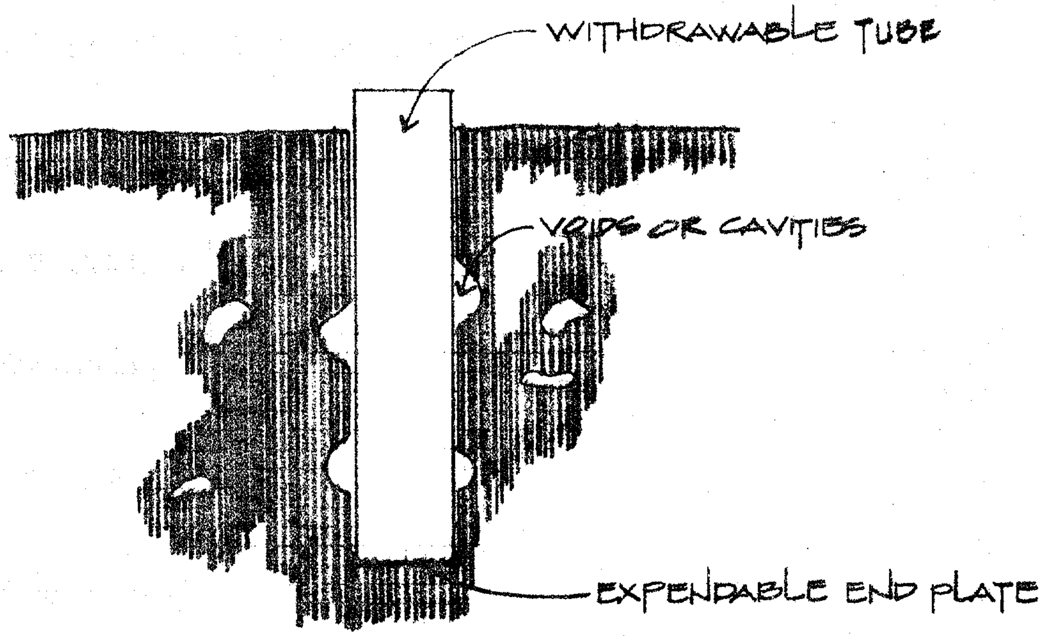
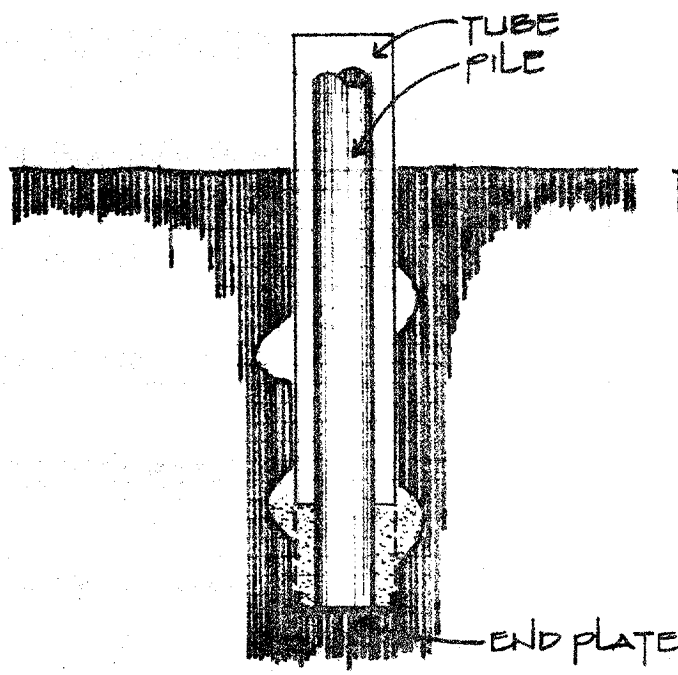
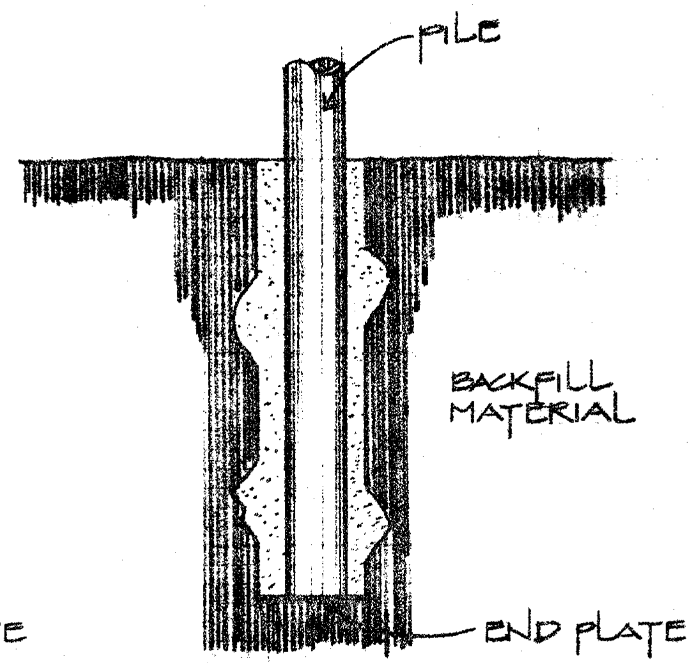


FIGURE 3-2. CONCEPTUAL DRAWING OF A BACKFILLED PILE - ALTERNATE B



(A) DRIVING WITHDRAWABLE TUBE WITH AN EXPENDABLE END PLATE

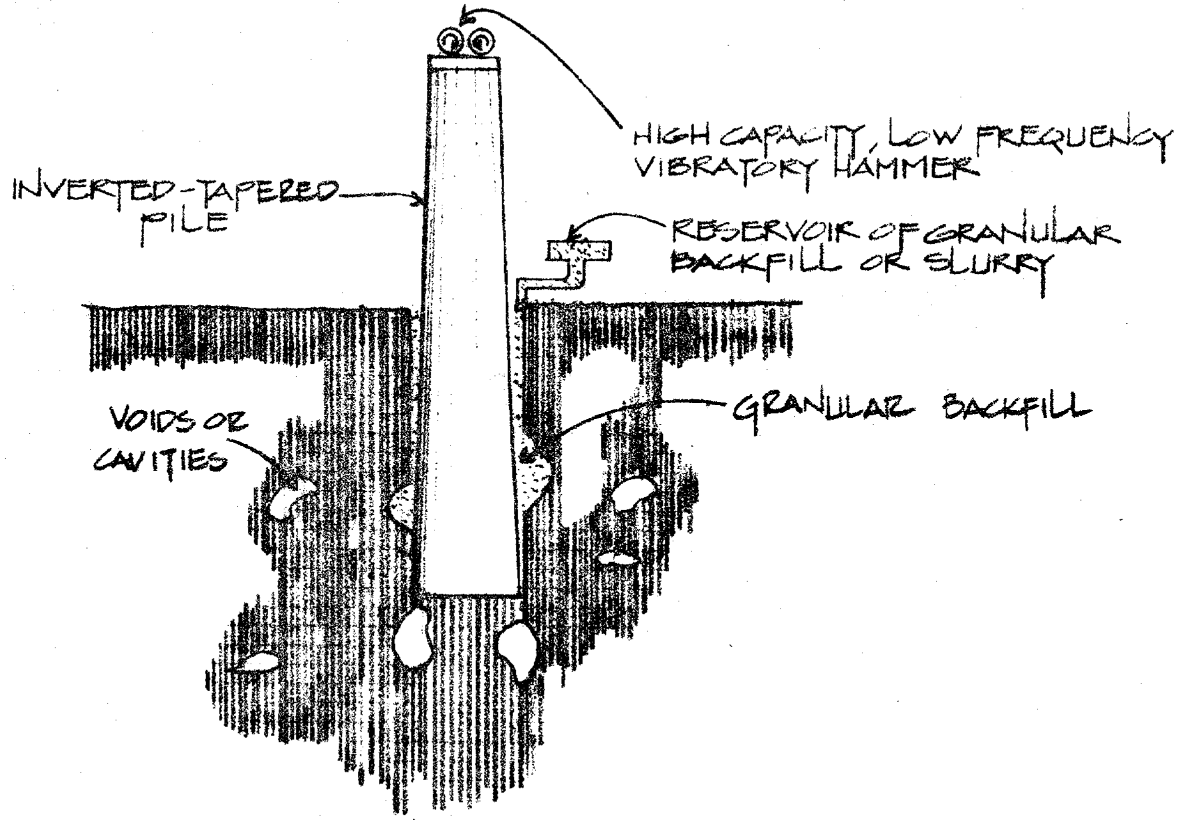




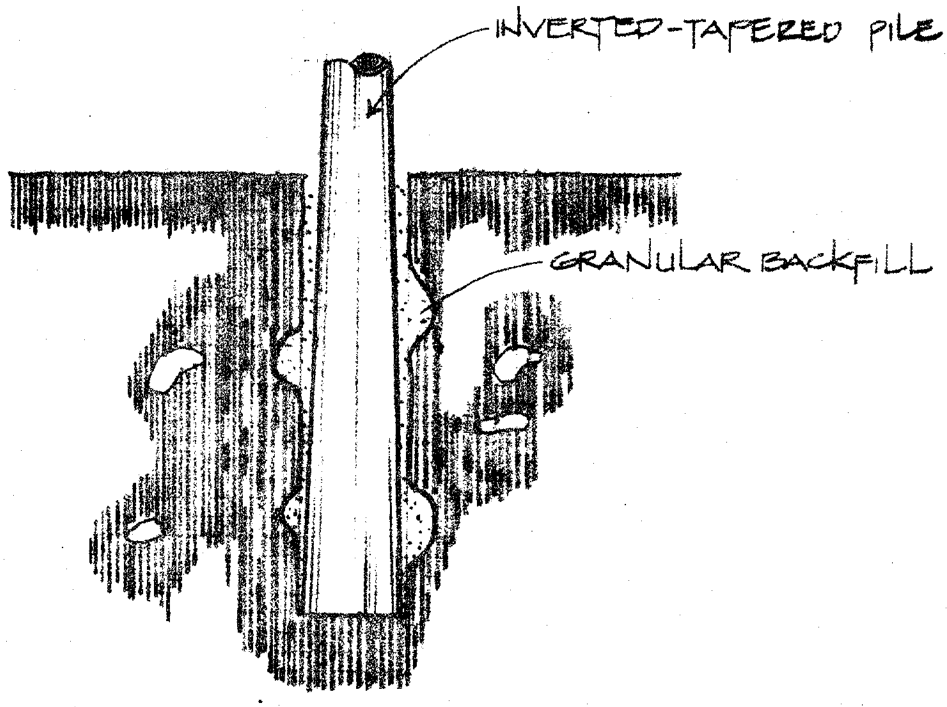
(B) INSERTING PILE, BACKFILLING AND COMPACTING WHILE GRADUALLY WITHDRAWING THE TUBE

(C) COMPLETED PILE

FIGURE 3-3. CONCEPTUAL DRAWING OF A BACKFILLED PILE-ALTERNATE C.

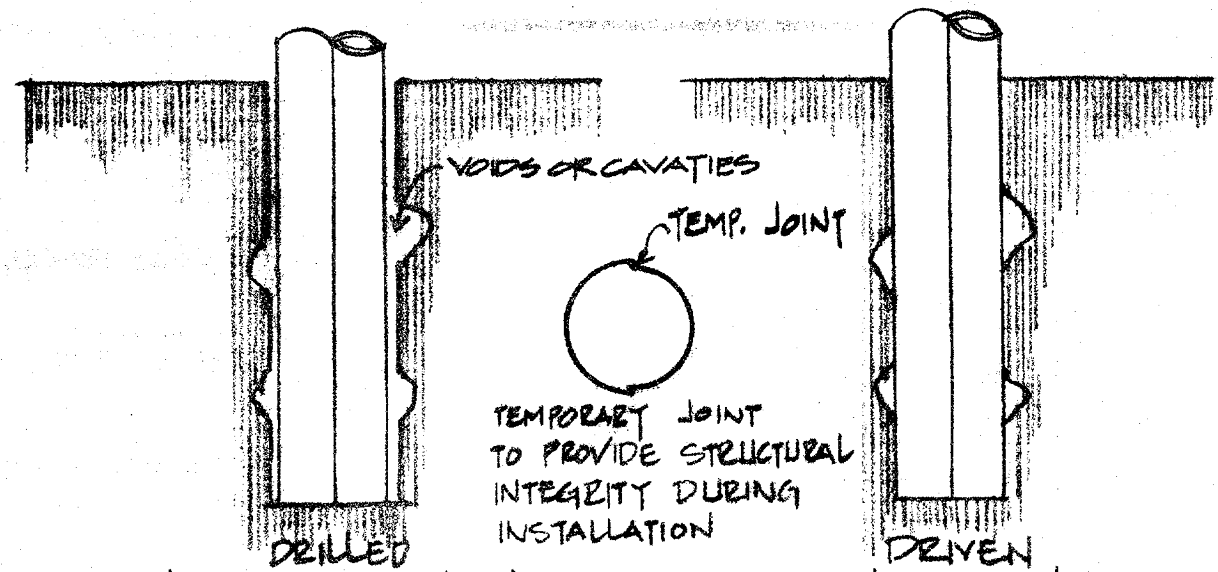


(A) VIBRATORY-INSTALLING THE INVERTED TAPERED PILE. BACK-FILLING AND COMPACTING WHILE VIBRATORY-PENETRATING



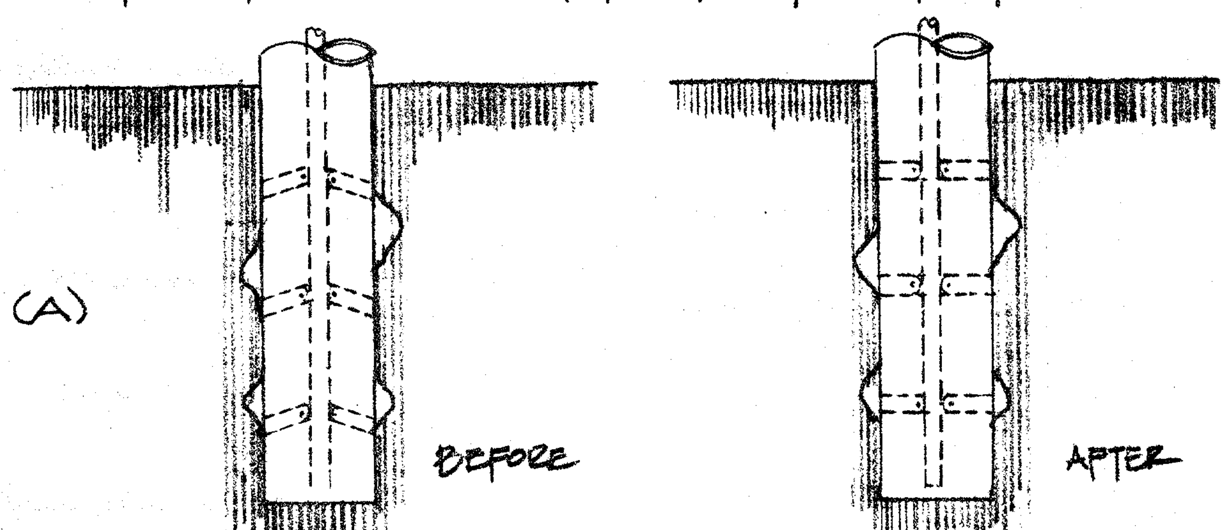
(B) COMPLETED SCHEME

FIGURE 3-4. CONCEPTUAL DRAWING OF VIBRATORY-INSTALLED BACKFILLED PILES



EXAMPLE OF MECHANICAL SYSTEM TO EXPAND THE PILE

(A)



(B)

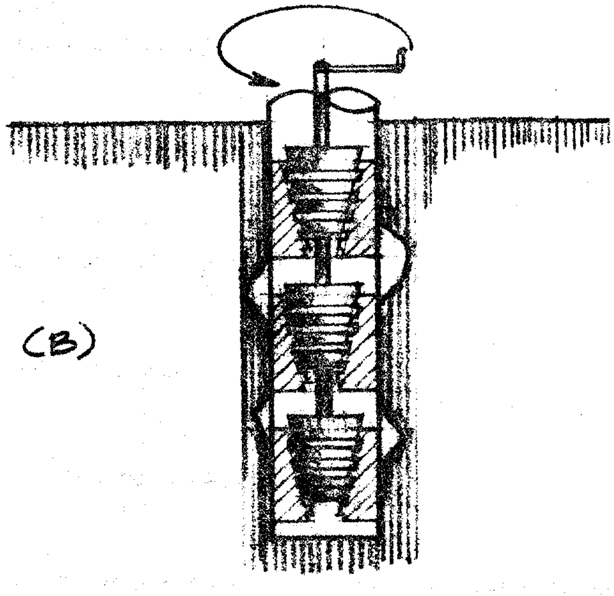


FIGURE 3-5 CONCEPTUAL DRAWING OF PRESSURIZED PILE-
ALTERNATE A

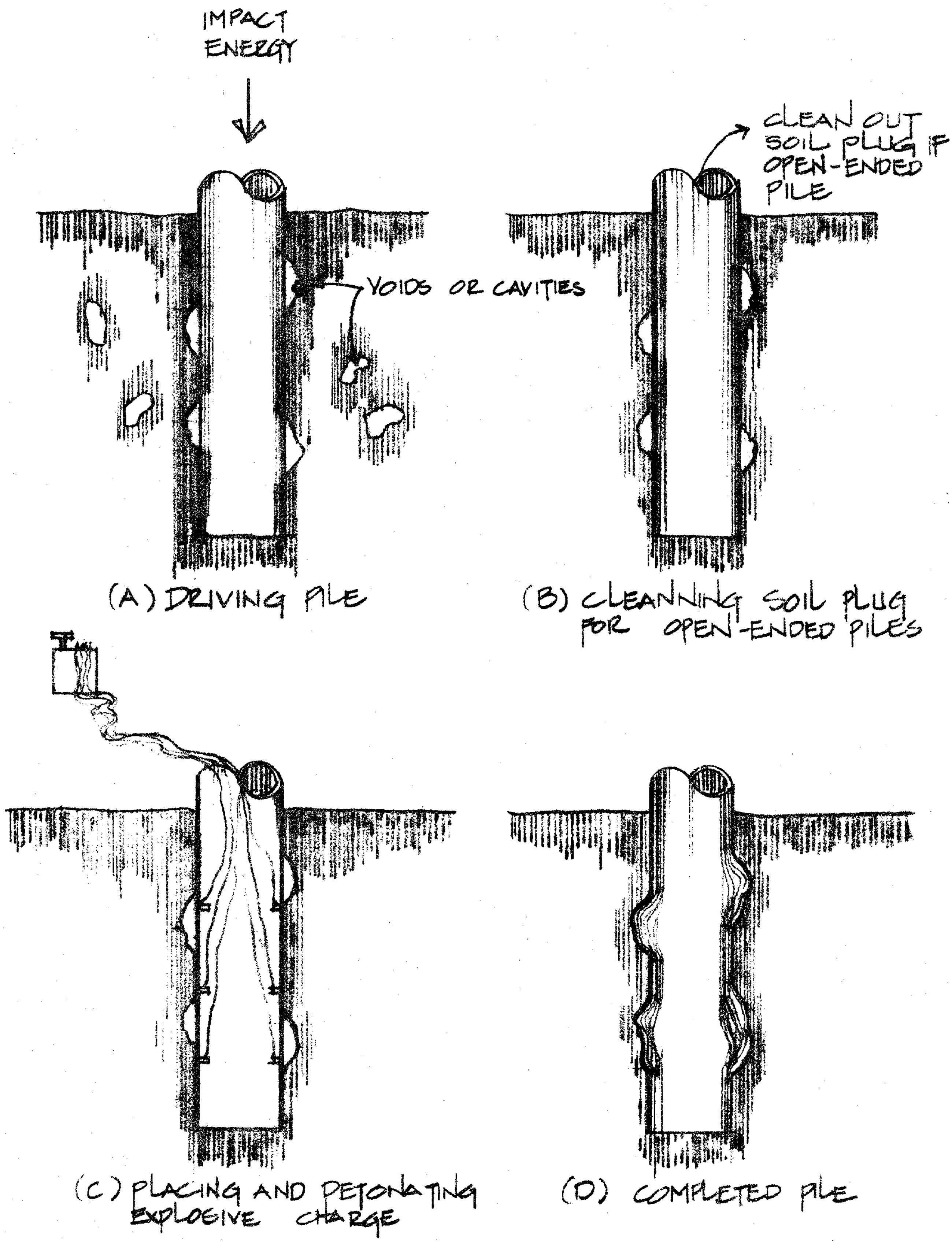
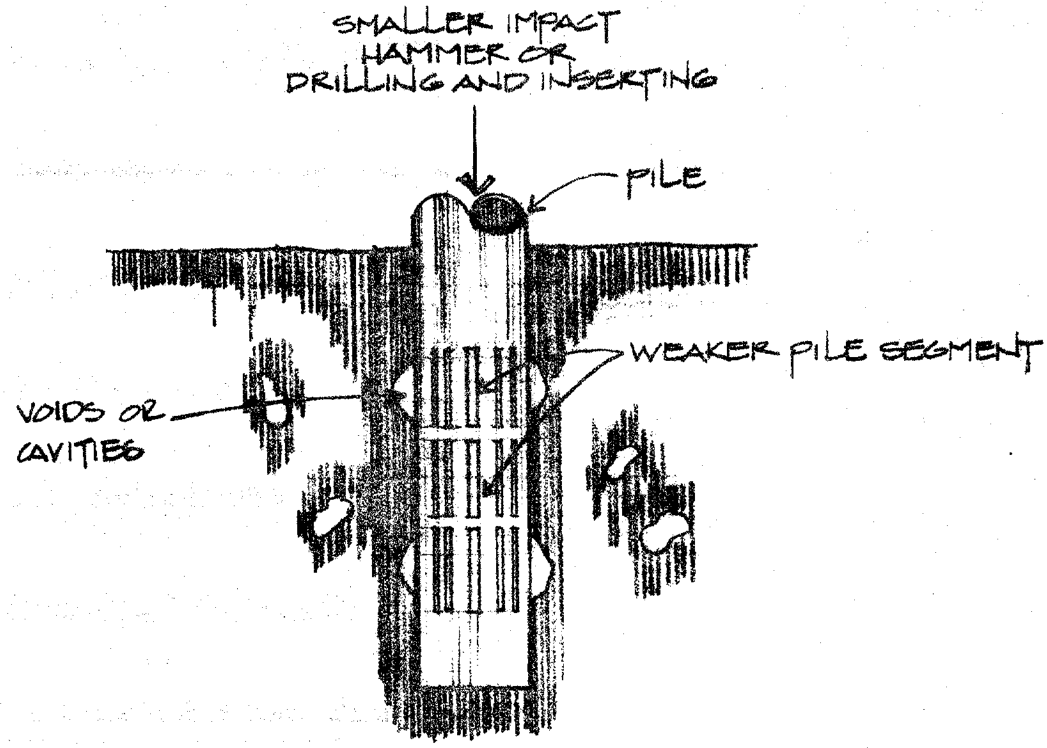
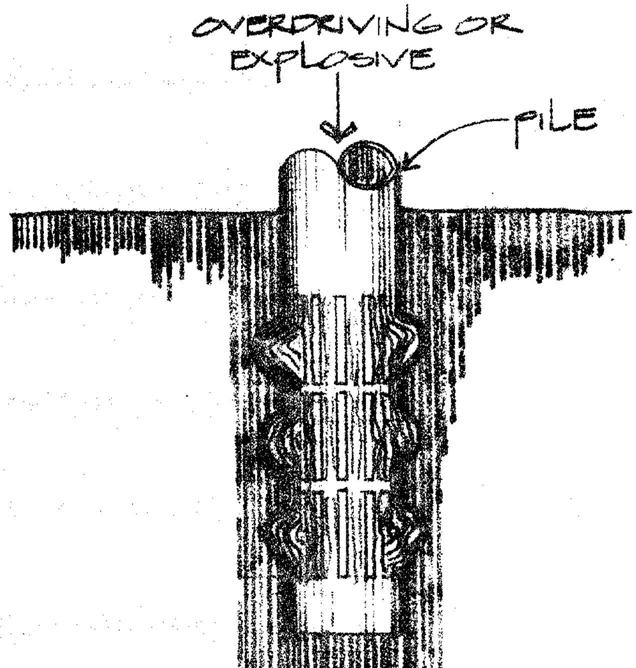


FIGURE 3-6 CONCEPTUAL DRAWING OF A PRESSURIZED PILE - ALTERNATE B

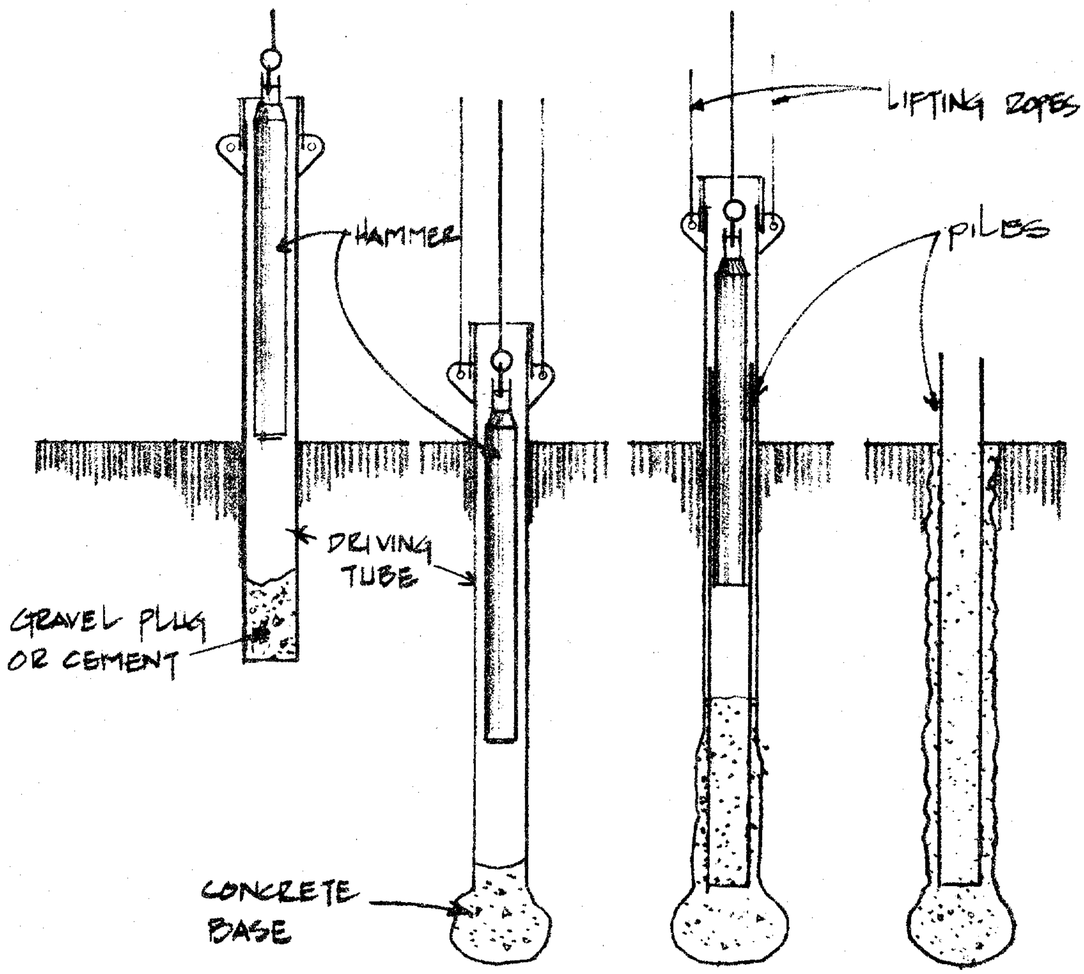


(A) INSERTING SPECIALLY DESIGNED PILE WITH WEAKER SEGMENTS



(B) COMPLETED PILES – BY OVERDRIVING OF DETONATING EXPLOSIVE TO BUCKLE WEAKER SEGMENT AND KEY INTO SEDIMENT OF CAVITIES.

FIGURE 3-7. CONCEPTUAL DRAWING OF PRESSURIZED PILE – ALTERNATE C.



(A) DRIVING WITHDRAWABLE TUBE AND PLUG

(B) COMPACTING TO CREATE A BULB BASE

(C) PLACEMENT OF PILE AND BACKFILL MATERIAL WHILE WITHDRAWING THE TUBE.

(D) COMPLETED PILES.

FIGURE 3-8 CONCEPTUAL DRAWING OF PILE WITH ENLARGED TIP (PET) - ALTERNATE A

BELLED OR EXPANDABLE TIP

CONVENTIONAL GROUT RELATED PROBLEM MAY CAUSE POTENTIAL PROBLEM HERE.

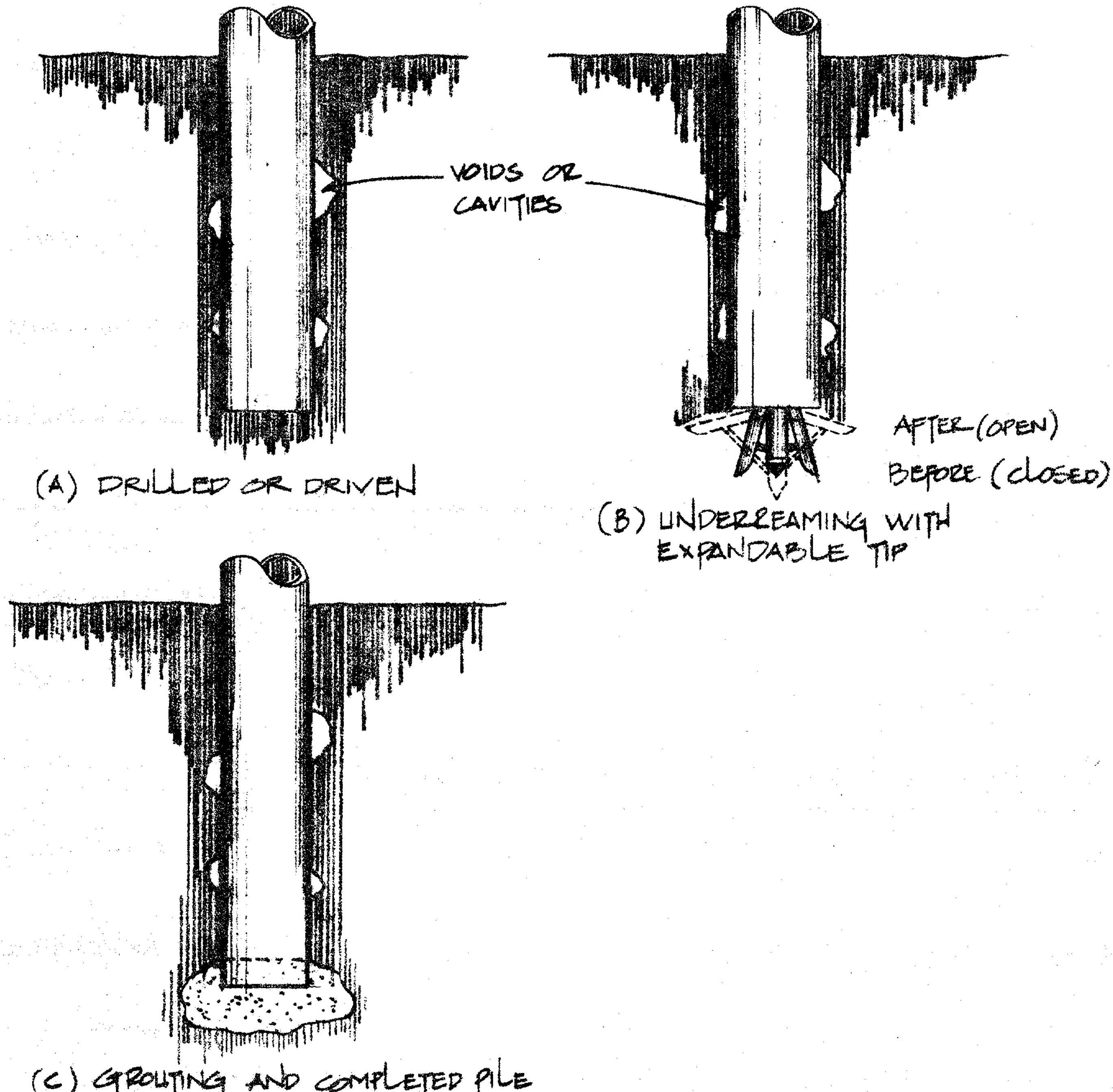


FIGURE 3-9. CONCEPTUAL DRAWING OF PILE WITH ENLARGED TIP (PET) - ALTERNATE B.

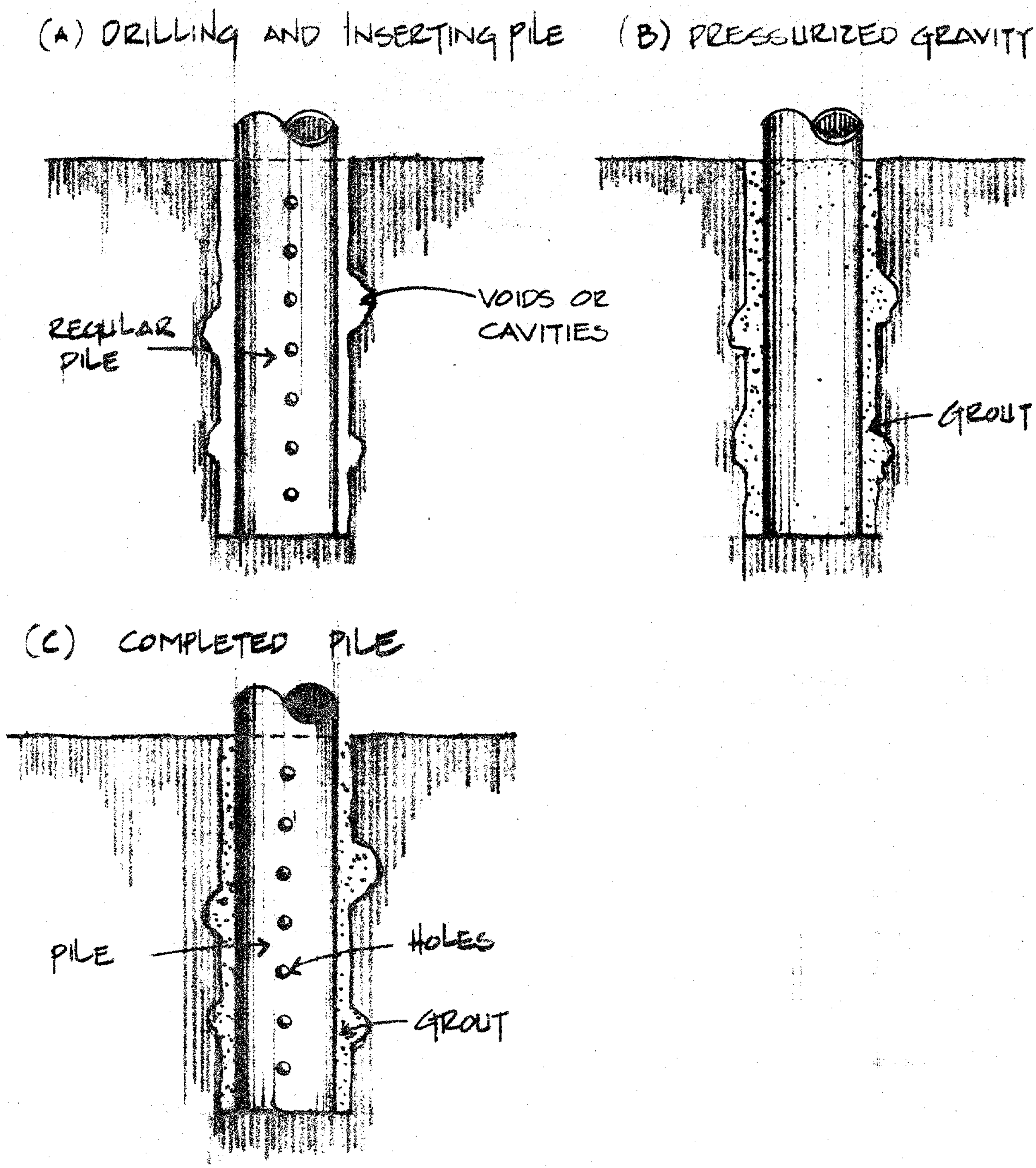


FIGURE 3-10. CONCEPTUAL DRAWING OF MODIFIED DRILLED-AND-GROUTED PILE.

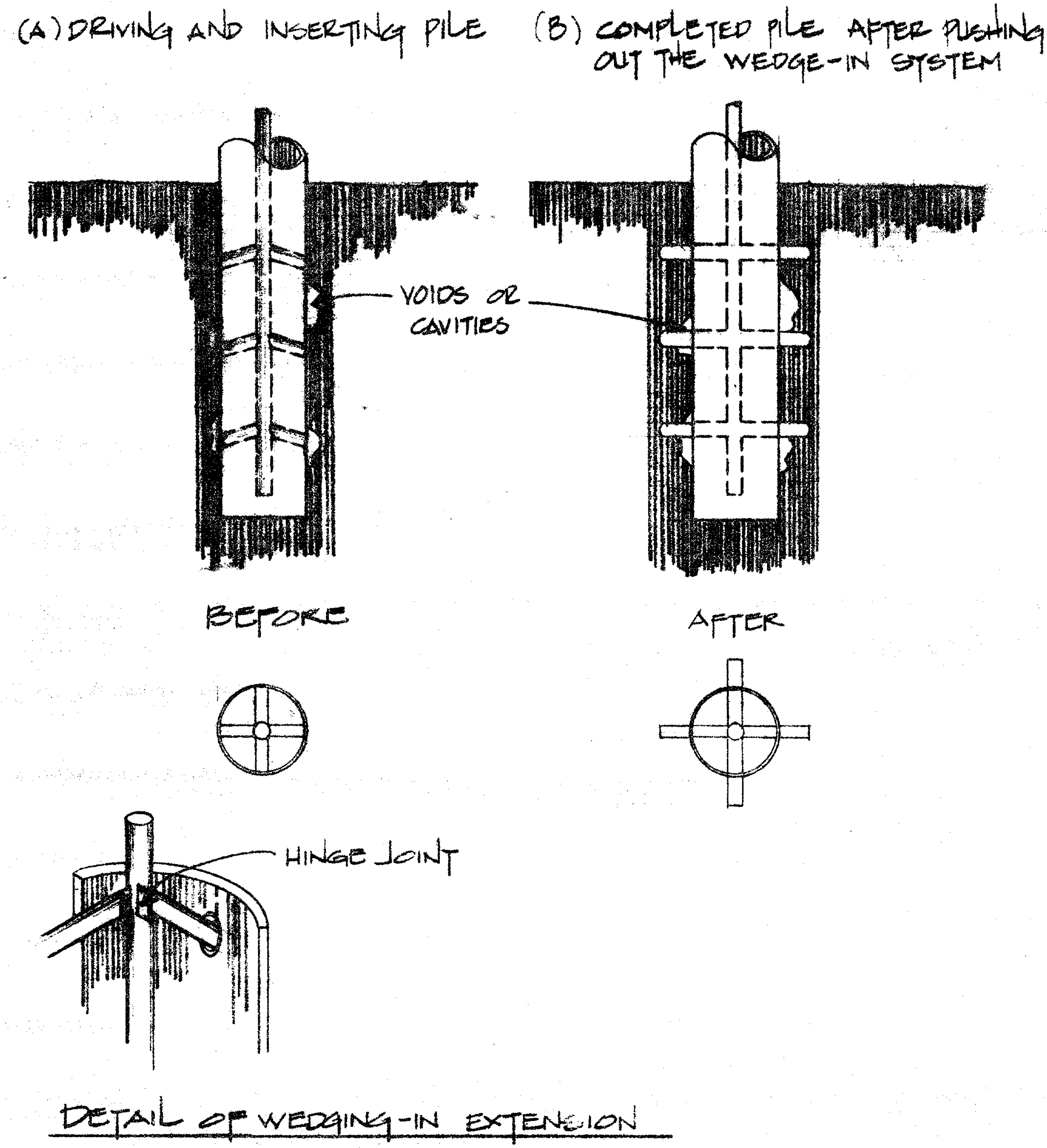


FIGURE 3-11. CONCEPTUAL DRAWING OF WEDGED-IN PILE.

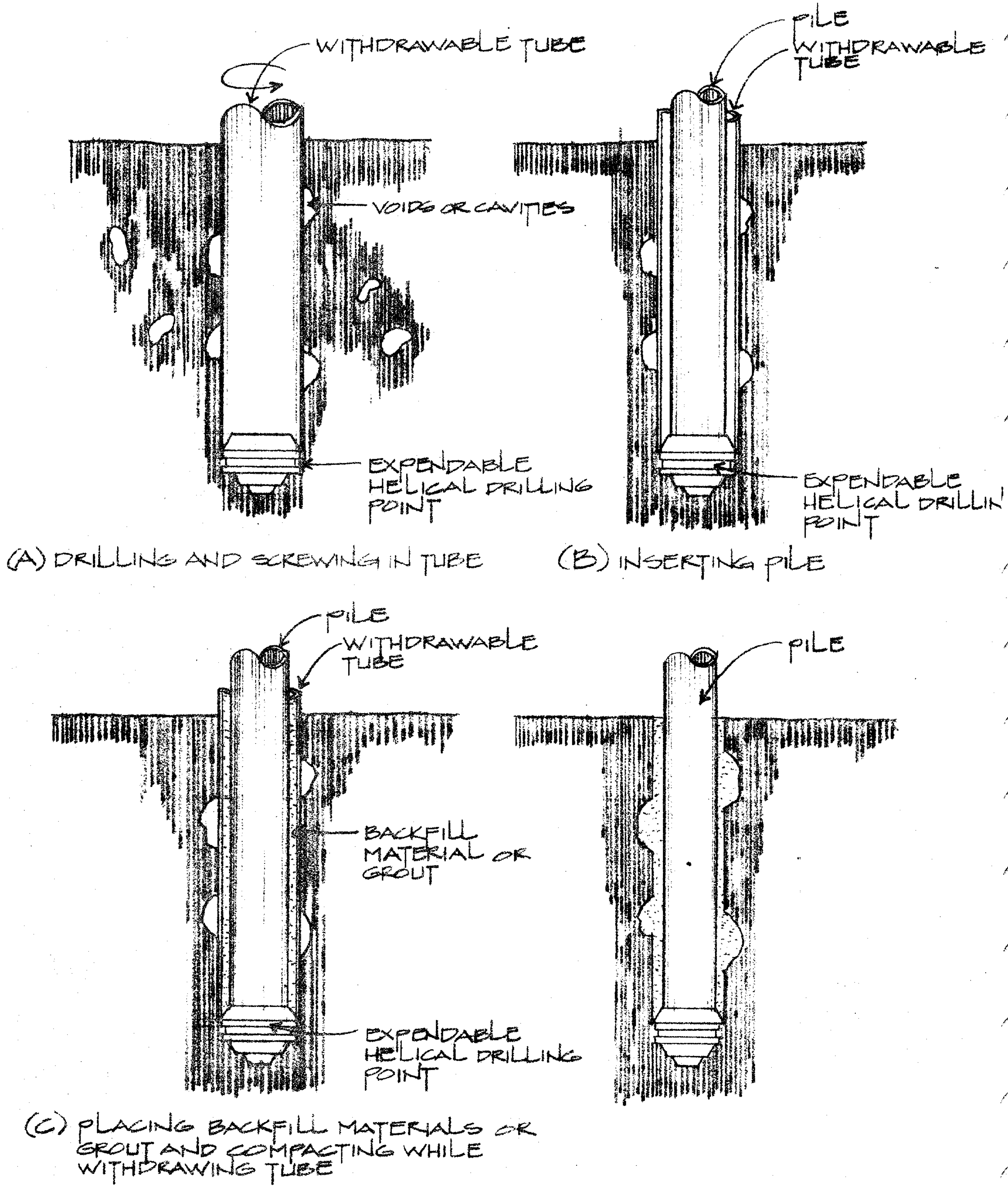


FIGURE 3-12. CONCEPTUAL DRAWING OF DRILLED AND SCREWED PILE

4.0 SUMMARY AND CONCLUSIONS

4.1 Summary

A review of the available GFM and engineering literature was performed to provide a brief description of current practice of piles in calcareous sediments and to provide a basis for conceptual development of improved piling systems.

Our knowledge of engineering behavior of calcareous sediments is meager and our understanding of pile behavior in calcareous sediments is even less. The complexity of depositional process, grain-structure arrangement, discontinuities and post-depositional alternation dictates that a significant spatial variation in composition and behavior of calcareous sediments can potentially exist even within a very small distance. The most significant parameters affecting the behavior of calcareous soils include (1) carbonate content, (2) grain crushability and associated volumetric changes, (3) degree of cementation, (4) index properties and (5) geologic process. Several relevant behavior aspects of calcareous soils are summarized as follows:

1. They are softer and more compressible resulting from grain crushing and volumetric change induced by confining or shearing stresses.

2. Their friction angles decrease with increasing confining pressure.

3. Prior to significant grain crushing, their friction angles are higher than or similar to the values for terrigeneous soils.

For nearshore and offshore application, long open-ended steel pipe piles are usually utilized in current practice. Installation techniques include (1) driving by impact hammer, (2) drilling and grouting, and (3) driving by vibratory hammers.

Present design methods rely heavily on either empirical approaches or expensive field pile load tests. Further work toward a better understanding of pile-sediment interaction mechanism for piles in calcareous sediment is necessary to develop improved design methods.

Several key behavioral aspects of piles in calcareous sediments were obtained based on limited experimental data and engineering judgment. These key aspects are summarized in Section 2.5 and were utilized in the conceptual development of improved piling system for calcareous sediment applications.

In addition to utilizing these key behavioral aspects, we placed emphasis on practicality, achievability and following proven techniques, wherever feasible in developing the improved piling systems described in Section 3.

In general, these improved piling systems incorporate one or a combination of the following features:

1. Increasing the effective lateral stress.
2. Enlarging the base area.
3. Eliminating or minimizing the sources causing low load carrying capacity.
4. Transferring load to the zone of soils where degradation is minimal.
5 Increasing contact area.

The following improved piling systems were conceptually developed:

1. Backfilled piles (BP)
2. Vibratory-installed backfilled piles (VBP)
3. Pressurized piles (PP)
4. Backfilled and pressurized piles (BPP)
5. Piles with enlarged tips (PET)
6. Modified drilled and grouted piles (MDGP)
7. Keyed-in piles (KIP)
8. Drilled and screwed piles (DSP)

Some of these schemes are presented with various alternates. The essential features of these systems are summarized in Table 4-1.

The developed conceptual piling schemes are, to a varying extent, different from conventional piling systems. These schemes and their effectiveness in improving load carrying capacity in calcareous sediments are yet to be proven. In addition, most of the procedures and equipment required for deploying these "improved" piling systems need some amount of further development.

After further development and confirmation tests (either in the laboratory by centrifuge tests or in the field), some of these developed schemes may be more applicable to certain types of calcareous sediments than others. It is anticipated that various schemes can be segmentized and categorized for calcareous sediments. The ultimate goal would be to achieve the ideal scenario that the pile makeup will consist of various standardized segments and features arranged to maximize its load carrying capacity in any specific type of calcareous sediments.

Appendix A presents a general description of the basic elements involved in planning and executing field pile load tests to demonstrate the feasibility of the above piling systems and to provide essential data for developing improved pile design methods.

4.2 Conclusions

The results of this study indicate the following:

1. Our knowledge of calcareous sediment behavior is meager and our knowledge of piles in these sediments is even poorer.

2. It is essential to further understand the pile-sediment interaction mechanism with a view toward improving current design methods, which rely heavily on empirical approaches or costly and site specific pile load tests.

3. The developed piling systems described in Section 3 can substantially improve the load carrying capacity of piles in calcareous sediments. The extent of improvement requires further determination.

4. Further developmental work is necessary to determine the feasibility and applicability of these systems for calcareous soil applications.

5. Cost consideration indicates that viability and applicability of these systems should be initially determined by centrifuge tests (Appendix B) to narrow down these schemes to a selected few promising ones for subsequent field load tests (Appendix A).

6. It is anticipated that the promising piling schemes can be segmentized and categorized for various calcareous sediments. The ultimate goal of further developmental effort would be to achieve the ideal scenario that the pile makeup will consist of various standardized segments or features arranged to maximize load carrying capacity in any specific type of calcareous soil.

TABLE 4-1. SUMMARY OF IMPROVED PILING SCHEMES DEVELOPED FOR THIS STUDY

Piling System	Alternate Figure No.	Primary Features	Applicable Calcareous Sediment Type	Principles of Load Carrying Capacity Enhancement	Estimated (Potential) Improvement in Load Carrying Capacity of Piles	Required Equipment**	Development Needs
Backfilled Piles	A/3-1	1. Drilling an oversized hole. 2. Inserting pile. 3. Backfilling the annulus with granular materials. 4. Compacting the backfill.	Non-cemented to highly solidified	o Increase lateral stress o Eliminate or minimize grain crushing effects.	Increase the skin friction resistance 50% to 500% or more.	o Rotary table, drilling equipment and accessories (All) o Slurry mixer and pumping equipment (All) o Equipment to densify backfill (Alternate A, Optional for B and C)	1. Suitable granular materials for backfilling (All) 2. Appropriate procedures and equipment to install the pile and to place the granular backfill (All) 3. Optimal sizing of annulus to eliminate or minimize soil arching effect (All) 4. Densification technique for the backfill (All) 5. Confirmation tests to determine its load carrying capability (All) 6. Pile behavior under static and cyclic loading (All) 7. Effect of mud contamination and ways to minimize them (Alternate A)
	B/3-2	1. Drilling an oversized hole with-drawable casing attachment. 2. Above Items 2 to 3. 3. Withdrawing casing and compacting backfill.	Same as above	Same as above			
	C/3-3	1. Drilling with-drawable tube with an expendable end plate. 2. Same as Items 2 and 3 for Alternate B.	Non-cemented to slightly solidified (weak rock)	Same as above.			
Vibratory-Installed Backfilled Piles	-/3-4	1. Installing a slightly invert-tapered pile by vibratory hammer. 2. Backfilling the gap with granular materials simultaneously.	Non-cemented to slightly solidified (weak rock)	Same as above.	Same as above	o Vibratory hammers and accessories. o Pumps and slurry mixer.	1. Items 1, 2, 5, 6 above. 2. Optimal pile configuration. 3. Degree of densification by vibratory hammers.
	A/3-5	1. Installing an expandable pile by drilling or driving. 2. Expanding the pile by hydraulic or mechnical system.	1. Depend on installation technique used. 2. Generally applicable in non cemented to slightly solidified.	o Increase lateral stress (All) o Increase bearing area (Alternates B, C). o Increase contact area (Alternates B, C).	Depend on the system which applies the pressure to the pile. Substantial increase is expected if the pressure can be maintained.	o Drilling equipment or impact hammer equipment. o Hydraulic or mechanical system to apply pressure.	1. Appropriate procedure and equipment to install pile. 2. Design of expandable pile. 3. Design of hydraulic or mechanical system. 4. Items 5 and 6 described for the backfilled piles.
Pressurized Piles	B/3-6	1. Installing pile by any available technique. 2. Detonating pre-arranged explosive charges and forcing pile shaft to key into sediment.	Same as above			o Pile installation equipment. o Detonation device.	1. Procedures and design of explosive charge attachment to the pile. 2. Explosive effect to the pile and its load carrying capacity. 3. Items 5 and 6 described for the backfilled piles.
	C/3-7	1. Installing pile consisting of segments of weaker sections. 2. Overdriving the pile to buckle the weaker segment and to force it to key into the sediments.	Same as above			o Pile installation equipment. o Impact hammers and accessories.	1. Pile design and development of weak pile segment schemes. 2. Required impact energy to buckle the weaker segments. 3. Items 5 and 6 described for the backfilled piles.

**Handling Equipment such as Vessel, Barge, Cranes, etc. is required for all piling systems.

TABLE 4-1 . (CONTINUED)

Piling System	Alternate Figure No.	Primary Features	Applicable Calcareous Sediment Type	Principles of Load Carrying Capacity Enhancement	Estimated (Potential) Improvement in Load Carrying Capacity of Piles	Required Equipment **	Development Needs
Backfilled and Pressurized Piles	Any combination of the above	Any combination of the above.	Depends on the scheme adopted, potentially applicable to all types.	Any combination of the above.	Any combination of the above.	Any combination of the above.	Any combination of the above.
Piles with Enlarged Tips (PET)	A/3-8	1. Driving a withdrawable tube with a plug. 2. Further driving the plug to form a bulb end. 3. Inserting pile and backfilling.	Non-cemented to slightly solidified.	o Increase end bearing area. o Minimize grain crushing effects. o Force the failure surface away from the pile way upon uplifting.	1. Increase skin friction (Alternate A). 2. Increase end bearing resistance (by the enlarged area) (All). 3. Increase uplift capacity (All). 4. Amount of increase depend backfill materials, hold area and sediment type.	1. Impact hammers (internal) and accessory driving equipment. 2. Withdrawable tube and systems to hold it stationary and to withdraw it (vibratory pile extractor). 3. Equipment to place concrete, grout or granular backfill.	1. Some development work in installation techniques, procedures and equipment. (All) 2. Relations between size of plug, size of bulb end and hammer requirement (Alternate A). 3. Procedures to place and densify concrete, or grout or backfill. (Alternate A). 4. Items 5 and 6 described for backfilled piles (All). 5. Optimal sizing of annulus (Alternate A).
	B/3-9	1. Installing pile by impact or vibratory hammers. 2. Underreaming to form a belled end. 3. Placing grout or cement to complete the pile.				1. Installation equipment. 2. Grouting equipment.	
	-/3-10	1. Advancing a perforated pile with a drill bit at the tip of drilling. 2. Pressure-grouting through the inside of the pile.	All	1. Reduce grain crushing effects. 2. Enhance skin friction resistance. 3. Increase contact area.	1. Increase skin friction resistance by 200% to 500% under static axial loading. 2. Expect some increase in skin friction under cyclic loading. The magnitude of increase requires further determination because of uncertainties in cyclic degradation behavior.	1. Attachment to match drill bit and the pile top. 2. Drilling equipment (rotary table, bits, and accessories). 3. Grouting equipment and accessories.	1. Same as Items 1 and 4 for the piles with enlarged tips. 2. Relationship between the configuration of perforation, grout pressure and sediment types. 3. Size of drill hole, etc.
Keyed-in Piles (KIP)	-/3-11	1. Installing a specially designed pile with mechanical keyed-in system equipped with lateral extension branches. 2. Push the branches through the pile and into the sounding sediments.	Non-cemented to highly cemented.	1. Increase contact area. 2. Increase bearing area. 3. Force pile to transfer load to zone of soils with little or prior degradation.	1. Increase axial compressive and pullout load carrying capacity. 2. Magnitude of improvement depends on pile makeup, keying-in system and sediment type, and is yet to be defined.	1. Pile installation equipment - either impact hammers or vibratory hammers. 2. Keying-in system. 3. Mechanical or hydraulic system to push in extension branches.	1. Design and implementation of keying-in system and pushing-in system. 2. Pile design. 3. Effects of various keying-in system to axial behavior and load carrying capacity. 4. Items 5 and 6 described for the BP piles.
Drilled and Screwed Piles	-/3-12	1. Rotating a piling tube equipped with an expendable drill point at the tip. 2. Inserting pile to drill point. 3. Grouting or backfilling the annulus between the pile and the tube. 4. When withdrawing the tube and compacting the backfill material.	Non cemented to slightly solidified.	Similar to the BP or the MDGP system.	Similar to the BP or the MDGP system.	o Hydraulic motor or rotary table and accessories. o Grouting or backfilling equipment. o Equipment to hold the tube and to compact the backfill material.	1. Some minimal development effort in equipment and installation techniques. 2. Optimal sizing of annulus between the tube and the pile. 3. Items 5 and 6 described for the PB piles.

** [illegible]iling E[illegible]ment s[illegible] Vess[illegible]ge, C[illegible] etc. i[illegible]ired fr[illegible]iling [illegible]ns.

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APPENDIX A

ELEMENTS OF FIELD PILE LOAD TESTS

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A.1 General

As described in Section 3 of the report, several improved piling systems were conceptually developed for potential applications in calcareous sediments. Although schemes similar to some of the developed concepts have been utilized elsewhere, these developed concepts are new in terms of calcareous sediment applications. Our knowledge of pile behavior in calcareous sediments is meager. There is a need to establish a well-documented data base which can then be analyzed with the objective of developing improved design methodology for these piling systems in various calcareous sediments.

The cost associated with the performance of field pile load tests for all the improved piling schemes developed in Section 3 of the report will be prohibitive. Instead, it is recommended that the viability and applicability of these conceptual schemes in various calcareous sediments be intially determined by performing laboratory load tests on instrumented model piles in calcareous sediment samples. It is important that all the essential features of the piling schemes, including configuration, backfill materials, installation technique, capacity enhancement systems and characteristics of calcareous sediments be simulated as closely as possible and the tests be performed under the anticipated static and cyclic loading conditions. To minimize size effects, it is further recommended that these tests be performed in a centrifuge. A brief description of basic principles of centrifuge tests are provided in Appendix B.

After laboratory model testing, a number of promising schemes among those developed can then be subject to field pile load tests to further demonstrate their feasibility for calcareous sediment applications and to establish rational design methods.

The following sections describe the elements involved in a field pile load test.

4.2 Elements of Pile Load Testing

Planning and executing a pile load testing program involves a number of elements with varying degrees of sophistication depending on the objectives. In general, the following elements are involved in planning and executing a field pile load test:

1. Establishment of the intended objectives of pile load tests.
2. Establishment of the required scope to accomplish the intended objectives.
3. Detailed characterization of the site.

4. Selection of pile load test location(s).
5. Development of a plan for the pile load test.
6. Design and fabrication of test piles.
7. Design, fabrication, calibration, and proof-testing of instrumentation package.
8. Design and fabrication of loading system.
9. Design and acquisition of data acquisition system.
10. Proof testing of overall test setup if feasible.
11. Installation of test pile and test setup.
12. Performance of the pile load test.
13. Data reduction and evaluation.
14. Documentation and reports.

A brief discussion of these elements are provided below.

A.2.1 Establishing Objectives and Scope

The objectives of a field pile load test program define the scope and requirements of the program. They affect all the elements involved in the program. The objectives should be defined as specifically as possible.

The primary objectives of a field pile load test in calcareous sediments are as follows:

1. To undestand the axial and lateral behavior of piles under various stages of loadings (installation, setup and subsequent static and cyclic loading).

2. To provide essential data to verify or refine pile design methods either for site specific or general purposes.

3. To verify installation techniques and their effect on pile behavior.

4. To evaluate the load carrying capacity of the piles.

After the objectives are established, necessary scope to accomplish the objectives are then planned and developed. The scope of work generally consists of the remaining elements required for planning and executing a field pile load test described in the previous section.

A.2.2 Site Characterization

Knowledge of the geologic and geotechnical characteristics of the site is a pre-requisite in any field pile load test program. Basic geologic data such as geologic history, sedimentation process, sediment conditions, presence or absence of discontinuities (caverns, sinkholes or solution channels), potential sediment instability feature, etc., are neeeded to (1) develop parameters potentially affecting the sediment characteristics and (2) establish the methods and extent required in geotechnical investigations to define geotechnical engineering characteristics of the subsurface sediments. As described in Section 2 of the report, geologic information is one of the basic index properties of calcareous sediments.

Geotechnical investigations in general, consist of a subsurface site investigations program and a laboratory testing program. The subsurface investigation program general consists of drilling, sampling and in situ testing. Because of variability in composition and engineering behavior of calcareous sediments, none of the available drilling and sampling techniques can be universally utilized for all calcareous sediments. Also, it should be recognized that calcareous samples obtained by present sampling techniques are likely to exhibit appreciable disturbance because of their susceptability to grain crushing, cementation-effects and physical degradation. A careful selection of drilling and sampling techniques is essential in minimizing sample disturbance effects.

Laboratory testing programs to determine the index properties, strength and deformation (static and cyclic) characteristics are required. The number and types of tests depend on complexity of site conditionns and stratigraphic profiles. The laboratory strength and deformation results should be carefully evaluated and judiciously used in engineering characterization taking account for the potential sample disturbance effects and the variability of in situ sediment conditions.

In situ test methods to obtain engineering properties in situ is essential in calcareous sediments. The potential of extreme spatial variation in engineering properties often justifies that more than one in situ test method be utilized for calcareous sediment. There exist various in situ test methods for calcareous sediment application. They include (1) cone penetration test (CPT), (2) pressure-meter test, (3) in situ vane shear test and (4) other tools such as geophysical surveys and experimental tools. The number and type of in situ tests depend on the extent of knowledge of the site conditions and their potential variability. They should be carefully planned and carried out.

The CPT is a valuable investigative tool for calcareous deposits. It is strongly recommended for use in characterization of any calcareous sediments. Beringer et al (1982) have utilized CPT data in conjunction with index properties to define calcareous sediment types and degree of cementation. They have also attempted to correlate sleeve friction and tip resistance data from CPT with pile load carrying capacity. However, because of lack of experimental data in different pile schemes in a variety of calcareous sediment conditions, the validity of this correlation requires further confirmation. However, its results and rational engineering judgement can be used for preliminary pile capacity assessment as well as for planning of field pile load tests.

The Earth Technology Corporation has developed an experimental tool designated as X-Probe (Figure A-1) and a 3-inch tool (Figure A-2). These instrumented tools are capable of measuring soil-pile friction, total lateral stress, pore pressure and axial displacement. In addition, the X-Probe is adaptable to regular CPT operation. The data from these tools provide a valuable information regarding axial pile capacity and axial behavior of piles in calcareous sediments. The information could be utilized in preliminary pile design and in planning the test setup for the field test program.

When planning and executing site investigations in calcareous sediment, it should be recognized that more than one drilling and sampling technique as well as more than one in situ tesing technique may be required because the extreme variability of calcareous sediments from one location to another. Flexibility and redundency should be normally required for calcareous sediment applications.

A.2.3 Pile Load Test Locations

Based on the site characterization findings, the location selected for the pile load test(s) should, of course, be representative of and consistent with the site conditions. The site selected should be easily accessible. The sediment characteristics from the ground surface to the intended penetration depth should be obtained and documented.

A.2.4 Planning Test Program and Procedures

Planning is the key to a successful completion of any field pile load test program. More planning effort means less delay. A test program involves a lot of items, anyone of which can easily malfunction or perform less than expected.

Planning a field test program consists of the following aspects:

1. Defining what is the load test program required to accomplish the objective - this should include the type and number of tests, pile makeup, installation method, loading characteristics and test data requirements.

2. Performing a preliminary assessment to estimate the ranges of pile behavior (response) under the test loading conditions - this should include the assessment of installability, load carrying capacity, pile displacement and any other items to be measured (for example, skin friction, tip resistance, lateral stress, pore pressure, etc.). This preliminary assessment is a necessity to estimate requirements for installation equipment, loading equipment, test setup, instrumentation and data acquisition systems.

3. Developing a checklist of all the necessary work required for the pile load test program. The list should also schedule and milestones.

4. Identifying the requirements and planning the details of installation, pile design, and fabrication, loading system and load frame, instrumentation program, and data acquisition system.

5. Establishing the test procedures of the pile load test program and subsequently modifying and improving them as the work progresses.

The test procedues should include detailed steps covering mobilization, installation, performing pile load tests and post-test evaluations. A contingency plan with potential remedial measures should also be developed to cover anticipated potential breakdowns of various elements.

A.2.5 Test Piles

The required makeup for the test piles have to be determined based on the project needs and piling schemes under consideration. The pile specifications (makeup and shape) and structural integrity (such as welding and joint integrity) require inspection and confirmations after test piles are designed and fabricated.

A.2.6 Instrumentation Package

The number and types of instrumentation have to be designed in accordance with project objectives, site conditions, the expected ranges of pile response to loading and other factors such as installation techniques, availability and achievability. Because of extreme variability of the calcareous sediments, the requirements of sensitivity, accuracy and full measurement ranges of the instrumentation package for pile load testing should be carefully designed, fabricated and calibrated. The results of preliminary pile response assessment (previous sections) and allowance for possible errors (factor of safety) should be implemented in the design.

The types of instrumentation required for a field pile load test in calcareous sediments should be sufficient to monitor the following aspects:

1. The effect of installations;

2. Axial and lateral pile-sediment interaction mechanism and responses including load carrying capacity and the load transfer mechanics for the pile under static and cyclic loadings.

For axial pile behavior, the instrumentation package should be capable of measuring the following parameters:

- shear transfer (skin friction) characteristics along the pile shaft;
- lateral stress and pore pressure at the pile wall;
- end bearing resistance at the pile tip;
- axial displacement of the pile (at pile top, along the shaft and at tip).
- magnitude and characteristics of the applied loading.

The X-Probe and 3-inch pile segment tools (Figures A-1 and A-2) are instrumented to measure the same parameters. Similar instrumentation packages can be designed and fabricated for the field pile tests.

For lateral pile behavior, the instrumentation package should be capable of measuring the following parameters:

- lateral response at the pile top (displacement and slope);
- lateral soil reaction (P) and lateral deflection (y) relation;
- magnitude and characteristics of the applied loading;
- lateral soil stress and pore pressure along the pile wall.

The P-y relationship for the pile is usually measured indirectly by monitoring the bending moment distribution along the pile then applying double integration to obtain deflection and double differentiation to obtain lateral soil reaction (Matlock, 1970). The lateral soil stress on pile and pore pressure measurements along pile shaft are optional but preferable. These parameters can provide a check to the indirectly obtained P-y relationship.

The durability of instrumentation package should be proof-tested prior to field applications. Proof tests in simulated environment similar to those anticipated in the field pile load tests program are necessary to insure a higher reliability.

Calibration of the instrumentation package should be performed in the laboratory, and after it is installed in the field. If feasible, periodic calibration before and after each pile load test sequence should also be performed.

A.2.7 Loading System

The loading system include the equipment and attachments to exert the intended loading magnitude and characteristics to the test pile(s). It usually include load test setup, loading devices and control equipment. The loading system depends on the scope and objectives of the pile load tests program. Figures A-3 to A-5 show some of the typical loading systems utilized elsewhere.

The loading system shown in these figures are deployed for tests on land. For near-shore and offshore application, different systems with similar principles can be erected if a representative site for pile load tests cannot be located on land.

A.2.8 Data Acquisition System

The extent and sophistication of data acquisition system depends on objectives, scope and site conditions. For example, if the objecive is to proof test the static allowable compressive working load on a pile using dead weight, minimal instrumentation and manual data acquisition may be needed. If the objective is to further understand the soil-pile interaction mechanism, a significantly more sophisticated data acquisition system for various items (such as shear transfer, loading control, displacement, lateral stress, etc.) would be required. The more automation utilized in data acquisition system, the less manual monitoring is required (i.e. less manpower).

A.2.9 Proof Testing

Proof testing of various test elements should be performed off site or in the field, if feasible. Proof testing is a valuable diagnostic tool in identifying potential deficiency and sources of potential problems. The added expense can be easily justified to avoid unnecessary and costly delay in the actual performance of a field pile load test.

A.2.10 Installation of Test Set-Up

Installation of test piles and test setup is one of the major sources for delay. Improper installation could damage the test pile and the instrumentation package and could potentially cause a costly delay in erecting the proper loading system. Because of variability in calcareous sediments, more potential problems in installation can be anticipated than those in terrigeneous sediment. Proper planning, execution and carefully-selected, installation equipment and techniques are the key to success. More than one installation method should be planned and made available during the installation phase for testing piles in calcareous sediments.

A.2.11 Performance of Pile Load Test

In general, the pile load test should consist of the following sequences:

1. Monitor pile responses during installation.

2. Perform axial compression or pullout tests immediately after pile installation to evaluate axial pile behavior prior to consolidation setup (optional).

3. Monitor pile response during consolidations setup.

4. After consolidation is nearly completed, perform a static axial load test (push or pull out) or a lateral load test to failure and then unload.

5. Monitor responses after static testing until most of the excess pore pressure is dissipated.

6. Perform a series of either one-way or two-way cyclic loading tests in cyclic increments to evaluate the cyclic response and cyclic degradation behavior of the pile.

It is important that loading should be applied in a displacement-controlled fashion, wherever feasible to avoid excessive displacement or damage to the test piles and loading system.

In performing the pile load test the established test procedures should be followed as closely as possible. In the process of performing pile load tests, refinements and modifications to the test procedures are the norms and not an exception. Preliminary data reduction process should be performed during the field tests to evaluate the validity of data, monitor the performance and check and modify, if necessary, the established test procedures. A successful pile load test should anticipate the unexpected, diagnose the observed problems, and provide necessary adjustments and remedial measures during testing.

A.2.12 Data Reduction and Evaluation

After the pile load test, data obtained from the field should be reduced for further engineering evaluations.

Engineering evaluations include the following items:

1. Understanding the observed pile behavior under various loadings.

2. Defining the modes of failure and associated load carrying capacity.

3. Providing design information.

4. Correlating these data together with engineering analysis to understand the soil-pile interaction mechanism with a view toward improved pile design methods.

5. Establishing improved and practical pile design methods.

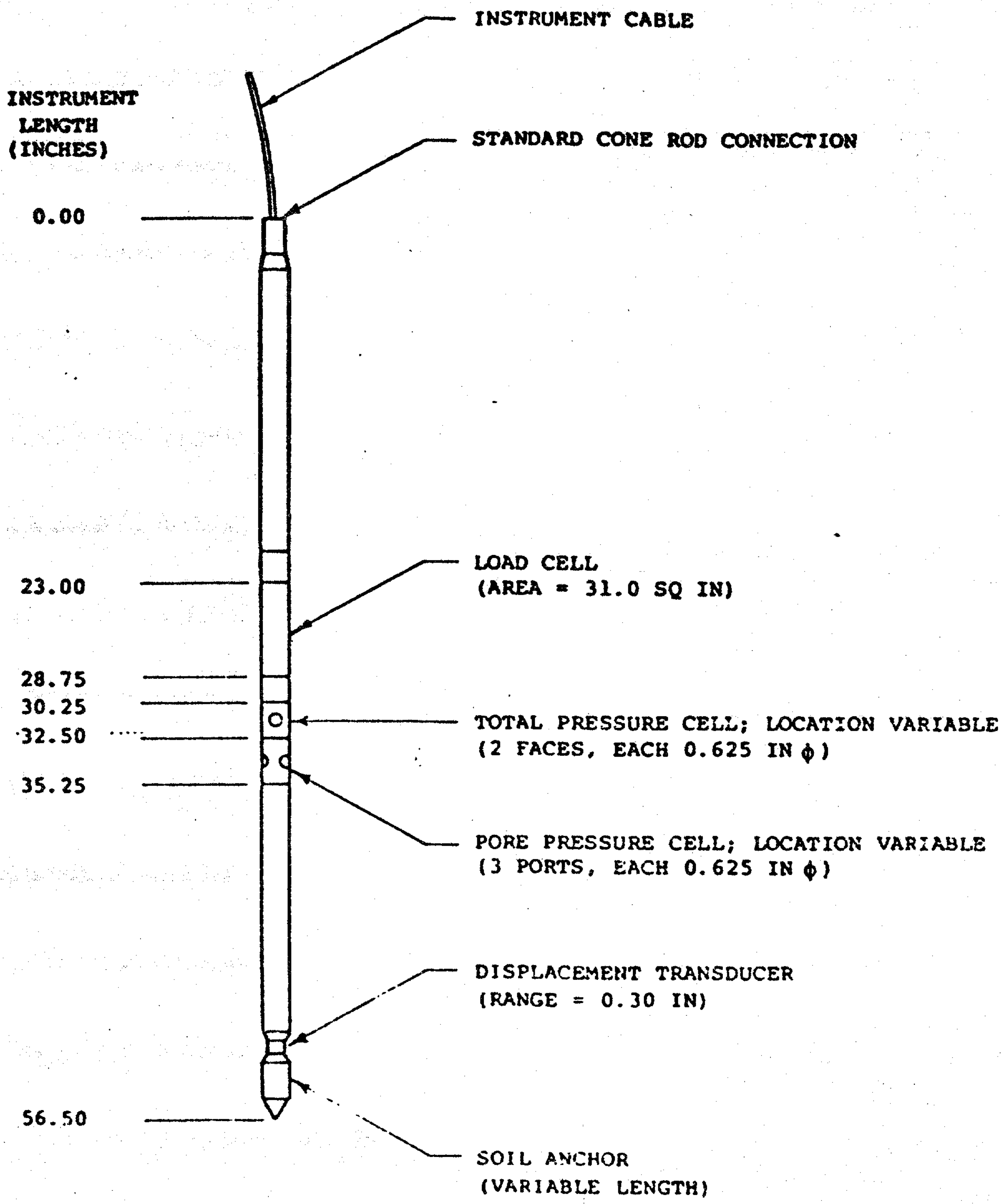


FIGURE A-1 DIAGRAM OF X-PROBE (1 IN. = 2.54 CM)

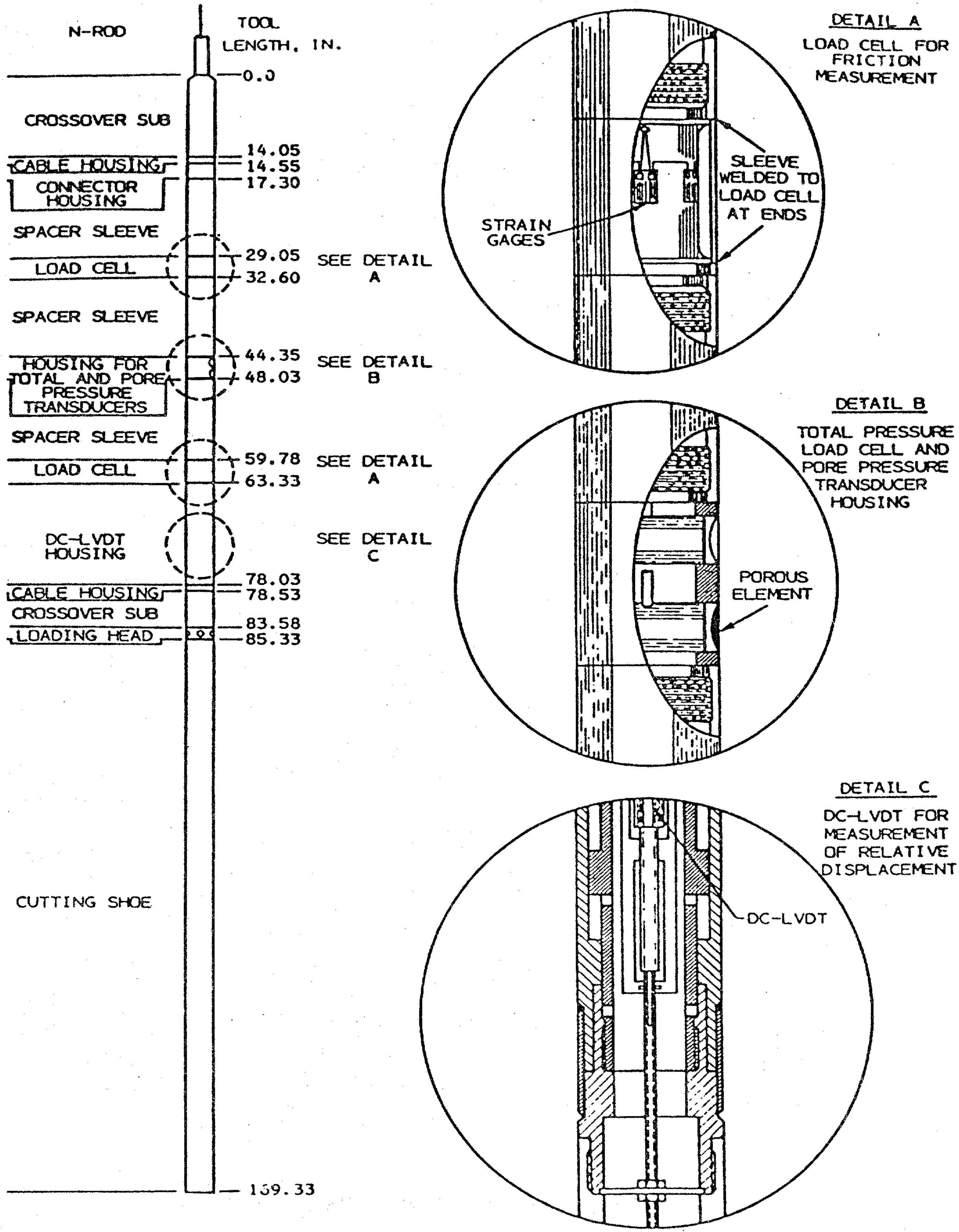
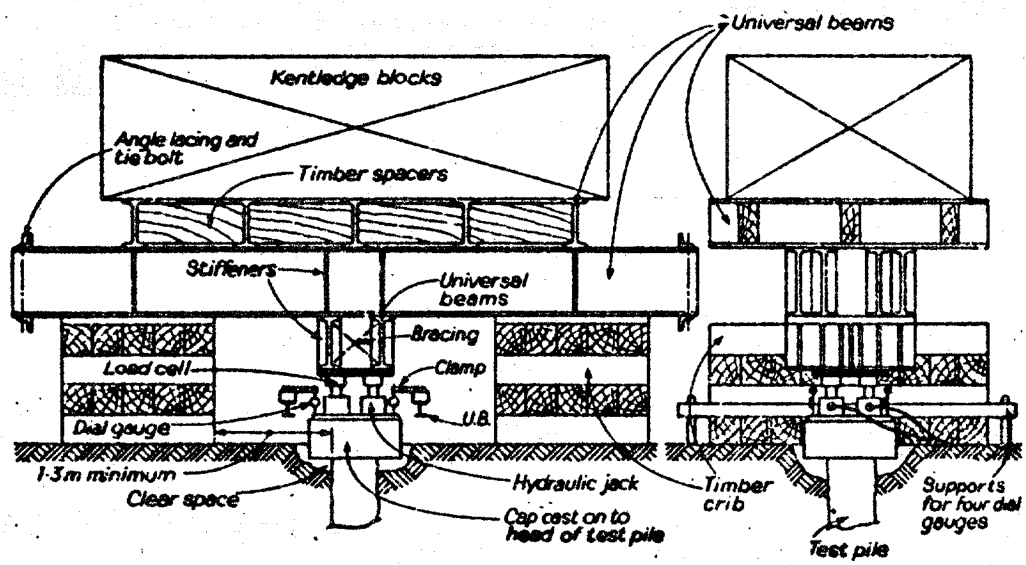
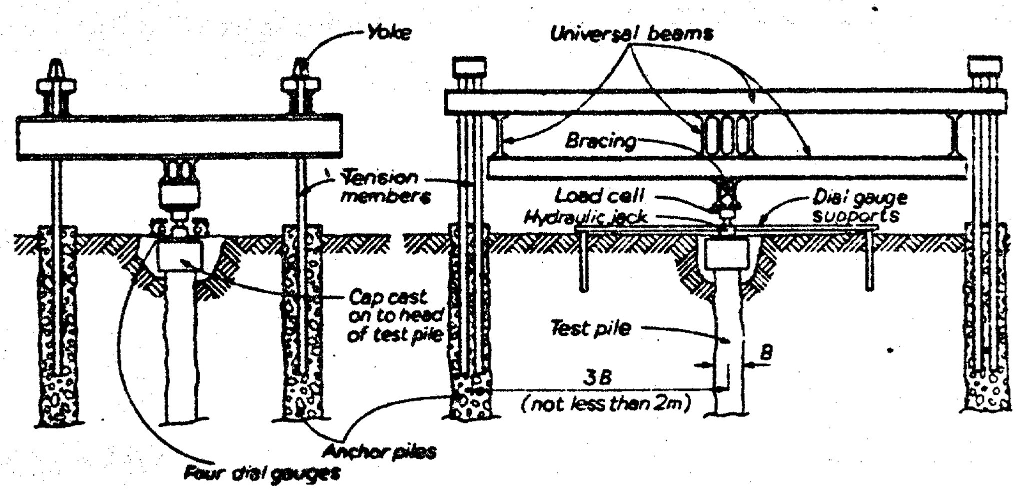


FIGURE A-2 DIAGRAM OF SMALL DIAMETER PILE SEGMENT (1 IN. = 2.54 CM)



(A) USING DEAD WEIGHT AND KENTLEDGE FOR REACTION



(B) USING PILES FOR REACTION AND HYDRAULIC LOADING SYSTEM

FIGURE A-3 EXAMPLES OF AXIAL LOADING SYSTEM AND TEST SETUP (AFTER TOMLINSON, 1977)

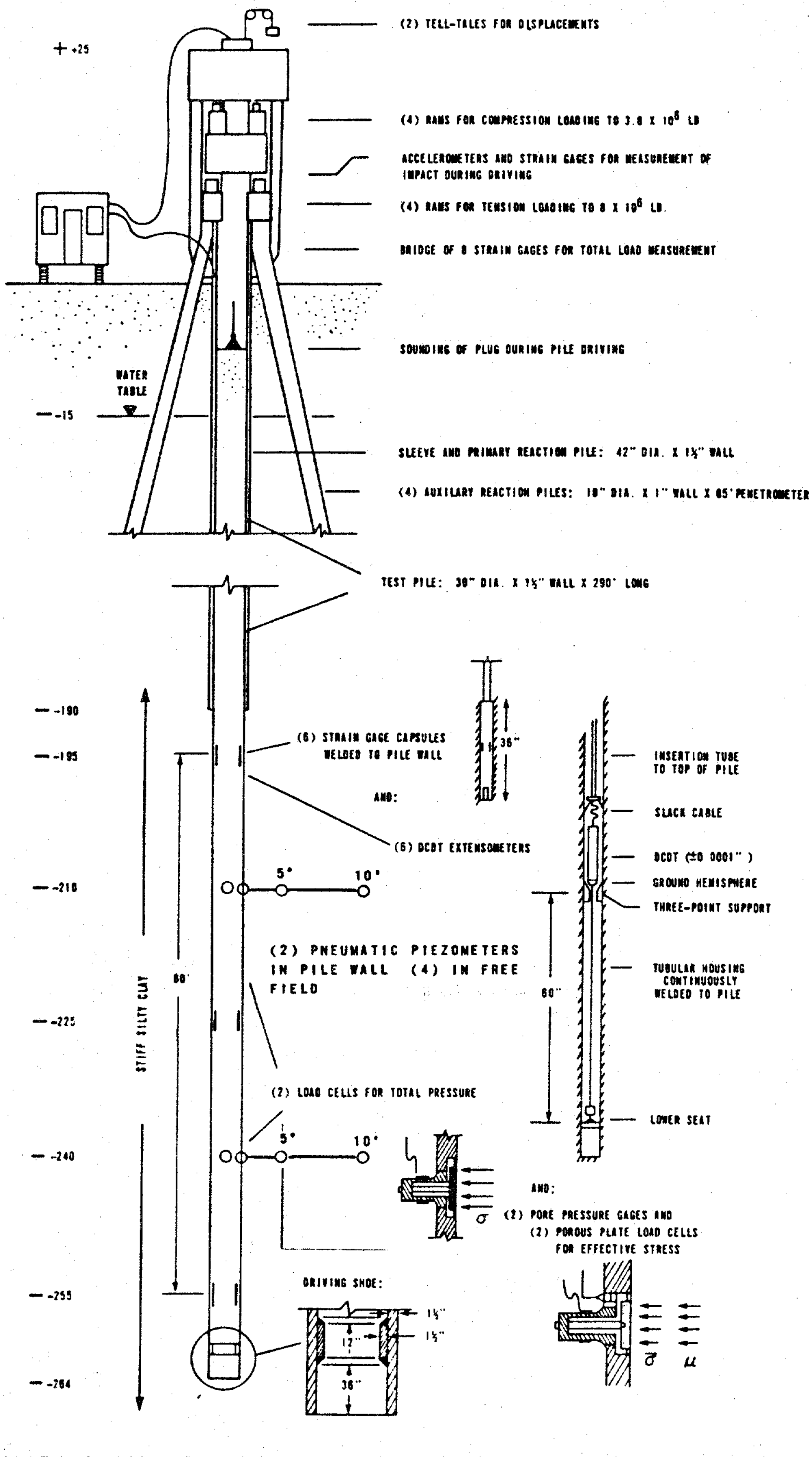


FIGURE A-4 EXAMPLE OF AXIAL LOADING SYSTEM AND TEST SETUP FOR AN INSTRUMENTED PILE LOAD TEST (MATLOCK AND LAM, 1980)

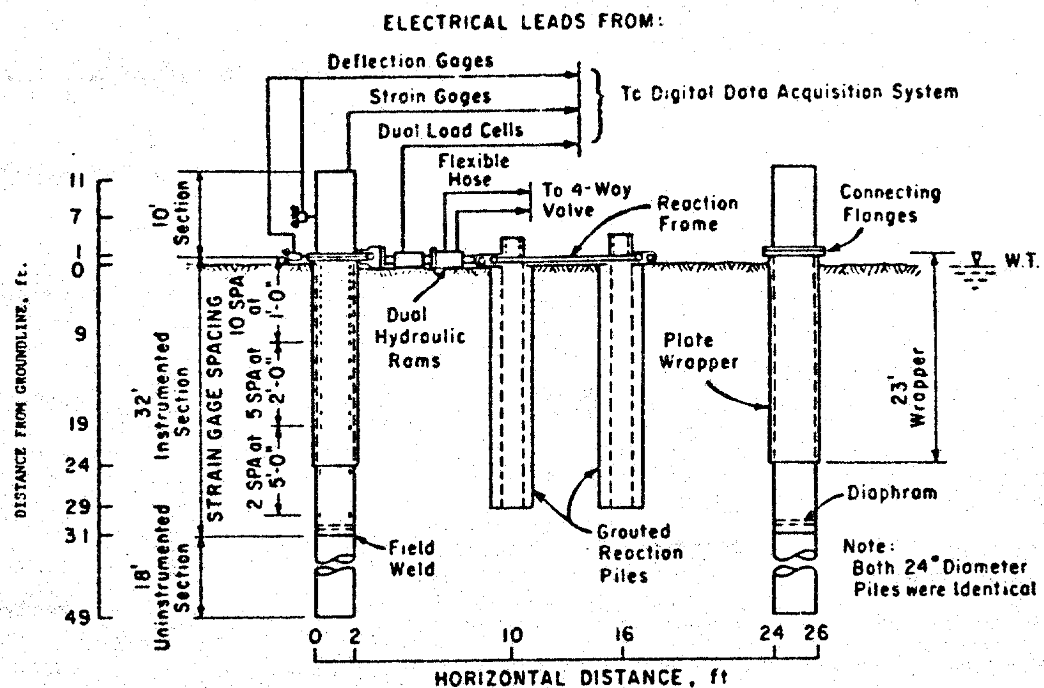


FIGURE A-5 EXAMPLE OF LATERAL LOADING SYSTEM AND TEST SETUP (AFTER REESE ET AL, 1975)

APPENDIX B

A BRIEF DESCRIPTION OF THE PRINCIPLES OF CENTRIFUGE TESTS

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A BRIEF DESCRIPTION OF THE PRINCIPLES OF CENTRIFUGE TESTS

B.1 General Principles

Centrifuges are currently used in geotechnical research and design projects to investigate the behavior of piles, gravity foundations and earth structures under prototype loading conditions. The centrifuge method involves construction of a "1/n" scaled model and subsequent testing this model in a centrifuge under a high acceleration level. The high acceleration is achieved by spinning the model at a constant velocity, as illustrated in Figure B-1. For a given rate of rotation, a constant acceleration in-line with the axis of rotation is developed. The magnitude of this acceleration, a, is defined by:

$$a = \frac{v^2}{r}$$

where v is the maximum linear velocity and r is the lever arm length. Typically centrifuges can apply 100 to 200 gs, which means 1/100 to 1/200 scale models can be tested.

The attractiveness of the centrifuge method is that stresses and strains in the model are identical to those in the prototype. Thus this testing method avoids problems associated with testing small-size models under earth's gravity. For materials with strongly nonlinear and stress-dependent behavior such as soils, the ratio of body forces to gravity forces has a significant influence on both the mechanism and magnitude of failure stress. Results of small-scale model test under earth's gravity are, therefore, generally questionable at best. Table B-1 gives a list of the relation between prototype and centrifuge model parameters.

B.2 Applications of Centrifuge Tests to Piling Systems

Centrifuge tests could be economically conducted to evaluate the viability and applicability of the improved piling systems in various calcareous sediments. The results of these tests would provide data necessary to narrow down the developed schemes to a few promising ones for further field pile load tests. The results can also be used to provide a data base for developing improved pile design methods for calcareous sediment applications.

It is important to similate the essential features of the developed piling scheme as closely as possible. This can be developed with litle effort in a laboratory controlled environment. It is also important that the centrifuge tests be performed on instrumented model piles for shear transfer, end bearing resistance and/or P-y relations under the anticipated static and cyclic loading conditions. This would require that the model piles be instrumented with strain gages and stress transducers.

Further planning is necessary to establish an optimal centrifuge test program for NCBC's needs. The successful experience gained from similar centrifuge pile testing programs (e.g., The Earth Technology Corporation, 1980; Scott, 1979; Scott et al, 1981) can be utilized to minimize the needed effort.

Quantity	Full Scale (Prototype)	Centrifugal Model at n g's
Linear Dimension, Displacement	1	$1/n$
Area	1	$1/n^2$
Volume	1	$1/n^3$
Stress	1	1
Strain	1	1
Force	1	$1/n^2$
Mass	1	$1/n^3$
Acceleration	1	n
Energy	1	$1/n^3$
Density	1	1
Energy Density	1	1
Velocity	1	1
Time		
In Dynamic Terms	1	$1/n$
In Diffusion Cases	1	$1/n^2$
In Viscous Flow Cases	1	1
Frequency in Dynamic Problems	1	n

TABLE B-1 SCALING RELATIONS FOR CENTRIFUGE TESTS

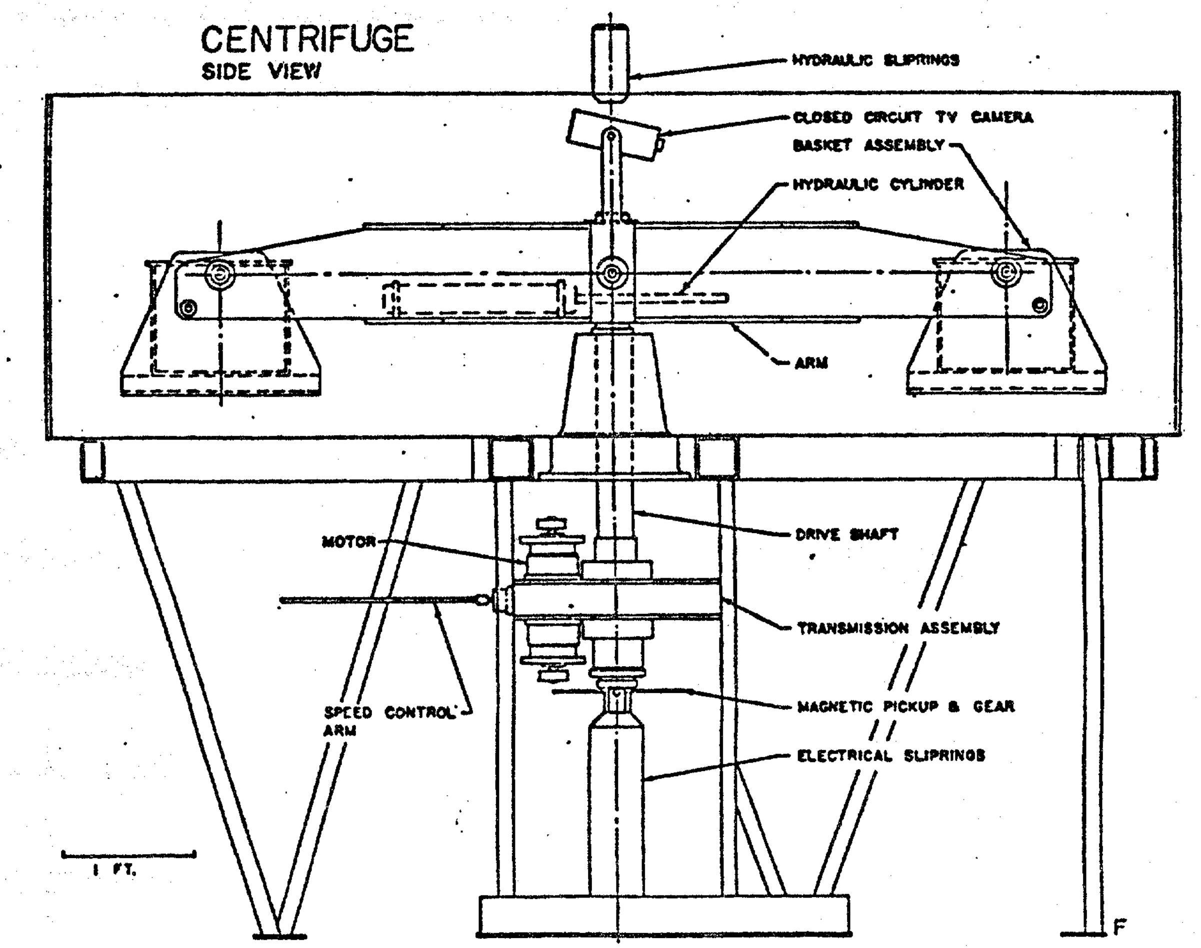

FIGURE B-1 SCHEMATIC DRAWING OF A CENTRIFUGE